Appendix G
Dye Studies

Appendix G. Dye Studies

Introduction

Four dye tracer studies were conducted in 2001, and one in 2002, to simulate the fate of the effluent plume after it reaches the designated plume trapping depths in Puget Sound. The principal objective of these studies was to assess the potential for effluent at the trapping depth to be transported onshore toward shallow beach areas in the vicinity of the proposed outfall sites.

The first round of dye studies were conducted during the weeks of February 5, March 12, May 7 and June 5, 2001. The February and May injection sites were in Browns Bay vicinity, and the March and June injection sites were in the Point Wells vicinity. The final dye study was conducted the week of February 4, 2002, from an injection site in the vicinity of Edwards Point.

In each study, Rhodamine WT fluorescent dye was injected into Puget Sound continuously for approximately one semi-diurnal tide period and tracked for several days at designated shoreline stations. Fluorometric procedures were guided by USGS protocol (Wilson, 1986). The measured dye concentrations at the shoreline stations may also be compared to the total dye discharge rate to assess dilution factors expected along the eastern shoreline of Puget Sound.

Methods

Detailed specifications and data for the five dye studies are presented in Table B-1.

Table B-1. Dye Injection Data

	Field Study				
	No. 1	**No. 2**	**No. 3**	**No. 4**	**No. 5**
Vessel	R/V Liberty	R/V Reflux	R/V Reflux	R/V Reflux	R/V Brenden D II
Location	Browns Bay	Point Wells	Browns Bay	Point Wells	Edwards Point
Position	N47^{o} 50’ 58.47”	N47^{o} 46’ 55.31”	N47–50’48.96”	N47–46’43.25”	N47°48’21.87”
	W122^{o} 20’ 36.72”	W122^{o} 24’ 12.66”	W122–21’29.28”	W122–24’40.59”	W122°24’40.69”
Water Depth	73m	79m	126	195m	171m
Dye Discharge Depth	5-11m	5-11m	22-28m	22-28m	55-61m
Date	2/5-6/01	3/12/01	5/7/01	6/5/01	2/4-5/02
Dye Start	16:55	07:15	05:30	04:50	14:40
Dye Stop	05:20	19:38	18:00	18:40	03:00
Discharged Volume (23.8% Solution)	167 L (43.0 gal)	187 L (48.2 gal)	179 L (46.2 gal)	190 L (49.1 gal)	355 L (91.6 gal)
Mass Dye Discharged	44.9 kg (99 lb)	50.2 kg (111 lb)	48.1 kg (106 lb)	51.1 kg (112 lb)	95.5 kg (210 lb)
Dye Discharge Rate	1.00 g/s	1.13 g/s	1.07 g/s	1.03 g/s	2.15 g/s

Dye

The tracer for these studies was Rhodamine WT liquid dye produced by Keystone Industries. The dye was shipped in 33-gallon HDPE drums at 23.8 percent solution, with a specific gravity of 1.13. Two drums totaling approximately 50 gallons were used in each study. The final study was an exception, in which four drums totaling approximately 100 gallons were used. The dye was injected directly from the supply drums in each study.

Dye Standards

Aliquots of dye were taken directly from the drums supplied by Keystone for laboratory analysis and calibration of the fluorometer. Dye standards of 0.092, 0.92, 9.2 and 92 ppb were prepared by King County laboratory personnel using serial dilution techniques recommended by Turner Designs (1991). All data were reported in units of ug/L (ppb) active ingredient (Rhodamine WT). The concentration of the undiluted dye was defined as 23% active ingredient (230,000 mg/L) prior to the preparation of standards. Multiple serial dilutions of this stock 23% solution were prepared down to levels expected in the samples. These solutions served as working calibration standards for the fluorometer.

Dye Injection Setup

The dye solution was injected into Puget Sound from a moored vessel. The R/V *Liberty* was used as the injection platform for the first study, R/V *Reflux* for studies 2 through 4, and the R/V *Brenden D II*. A schematic diagram of the injection system is shown in Figure G-1.

A 500-gph centrifugal pump was used to circulate ambient water onto the vessel deck, where it was combined with the dye. The dye was injected into the circulating ambient water with a progressive-cavity sample pump set and calibrated at a rate of approximately 3.8 gallons per hour (gph) for the first four studies, and 7.4 gph for the fifth study. The dye and circulating seawater solution were then discharged at selected depths through a 6-m long vertical diffuser. The dye solution at the point of discharge was at a concentration of approximately 1.8 ppt (1,800,000 ppb) after dilution with the recirculating ambient water for the first four studies, and double for the last..

Hourly CTD casts were obtained from the moored injection station to document the density of the dye solution versus the ambient density at the diffuser depth. Dye discharge was monitored hourly by measuring down to the surface in the dye container at hourly intervals. Flow in the system was also monitored hourly to ensure continuous injection over the specified period.

Dye Injection Stations

Two general outfall areas were selected for the 2001 studies. The first injection site was in the Browns Bay vicinity at a water depth of 73 m for the February study (all cited depths are MLLW datum). The second study in March was in the vicinity of Point Wells at a water depth of 79 m. The Browns Bay site was revisited for the May study, but at a deeper water depth of 126 m. The fourth study in June was repeated at the Point Wells location at a greater depth of 195 m.

The fifth study was conducted from a dye injection station at a water depth of 171 m in the vicinity of Edwards Point.

Rhodamine WT fluorescent dye was injected at the expected trapping depths of candidate outfall sites selected for the tracer studies. The dye diffuser was set at a fixed depth of 5 m at the top, and 11 m at the bottom, for the first two studies. Diffuser depths for the third and fourth studies were 22 m at the top of

the diffuser and 28 m at the bottom. Diffuser depth for the fifth study near Edwards Point was 55 to 61 m.

Dye Injection Schedule

Each dye injection period was designed to cover approximately one semi-diurnal tide cycle of 12.4 hour duration. Larger-than-average amplitude tides were chosen in order to capture conditions likely to produce maximum tidal excursion distances. The first four dye injections were initiated at a high water stand, continuing through a large ebb to near-zero MLLW tides, and through the ensuing flood to the following high water stand. The fifth study was reversed, with the injection beginning and ending near the low water stands. The fifth dye injection was also conducted during smaller amplitude tides than the previous four.

Shoreline Sampling Stations

During dye injection and over the following four days, water samples were obtained at established shoreline sampling stations on the eastern shoreline of Puget Sound. Shoreline sampling stations visited in the dye studies are shown in Figure G-2.

Shoreline samples were obtained in two ways. Autosamplers were established at locations where the equipment could be set up. The locations where autosamplers were used were the Meadowdale Marina, Edmonds Ferry Dock, and Edwards Point pier. Additional autosampler stations were set up for the fifth study. Samples were automatically obtained at 30-minute intervals for the duration of each field study. King County personnel maintained these stations and refreshed the sample bottles daily. Collected samples were stored in dark containers and delivered to the King County conventionals laboratory.

Two-person King County crews visited the remainder of the shoreline sampling stations via small craft (whalers and zodiacs). Water samples were obtained manually by dipping bottles to arm's depth near the shoreline. Shoreline stations were visited at about hourly intervals. Samples were stored and transported similar to the autosamplers.

Field Fluorometry

Direct plume measurements were also obtained in the farfield from a boat equipped with a towed fluorometer during each tracer injection period. . A Seapoint Rhodamine fluorometer (S/N SRF 4123) connected to a Seabird SBE 25 CTD was towed behind the ship. Position data was simultaneously recorded from the ship's GPS system. The fluorometer/CTD package was towed by a hydraulically driven hydrowire, allowing real time data to be displayed onboard. Vertical position was controlled by adjusting the length of hydrowire.

A single point calibration (in addition to a blank) of the fluorometer was made prior to each dye study using a 0.92 ppb standard. Based on observations of the natural background fluorescence, a detection level equivalent to 0.022 ppb was established.

Interference was observed with the fluorometer when it was towed within the ship's prop wash. Small air bubbles create erroneously high readings in the fluorometer. This effect appeared to be evident as deep as 1.5 meters below the surface, depending on ship speed and the location of the CTD relative the ship. As a result, data values within 2 meters of the surface were usually removed before analysis.

Laboratory Calibration and Method Detection Limit

The laboratory analyses of dye standards and field samples were made with a Turner Designs Model 10-AU set up in the discrete sampling mode. A single point calibration (in addition to a blank) was performed using a 0.92 ppb standard. Continuous calibration verification samples, check standards, method blanks, and lab duplicates were analyzed at a frequency of 1 in 20 samples to verify the calibration and overall method performance throughout the study.

A method detection limit (MDL) of approximately 0.020 ppb had been previously established and this limit was adopted for use in this study. However, a more practical reporting detection limit (RDL) of 0.040 ppb would better define the level at which greater confidence can be expected in the reported results. Inherent variability in the method below this level can contribute to significantly lower precision observed for lab duplicates.

Initial analysis was performed on samples that were collected prior to release of the dye during study No. 3. These results were used to estimate background fluorometer reading that could be expected for this matrix type. The results varied from 0 to 0.032 ppb. These results were similar to the background levels observed in the previous dye study. The previously established background threshold of 0.040 ppb was therefore considered an appropriate level to maintain. Below this level, variability in the method coupled with the estimated background levels makes it difficult to ascertain the presence or absence of dye.

All data collected below 0.040 ppb were therefore considered at background levels and no further action was considered necessary. Results above this level were associated with the presence of dye. These results were therefore subjected to greater scrutiny to ensure an interference was not responsible.

Laboratory QA/QC

The assigned LIMS login number, the fluorometer reading in units of ug/L Rhodamine WT, and the date of analysis are provided for each sample. Along with the original samples received, the results of analysis for all applicable method blanks, check standards, and lab duplicates were provided in spreadsheets. The percent recovery for all check standards and lab duplicate relative percent differences were also reported.

The “Comments” field in the results spreadsheet was used to record the qualifier “filtered” or “unfiltered” for each reported result. This designated whether the final result reported on the attached spreadsheet was generated from a filtered or unfiltered sample aliquot. A result was reported from an unfiltered sample if the result was below the estimated background threshold of 0.040 ppb or the sample had a turbidity of less than 0.8 NTU. Alternately, a result was reported from a filtered sample if the original unfiltered result was above the background threshold and the sample had a turbidity greater than 0.8 NTU. Unfiltered values in this category were not used in subsequent data presentations or calculations.

Turbidity Standards

The King County lab prepared a series of turbidity standards in the absence of Rhodamine dye and measured fluorescence with a Turner Model 10-AU fluorometer. The results are shown in Figure G-3. There was a clear linear relationship between turbidity and fluorescence in the range of 2 to 50 NTU.

The turbidity standards were then spiked with 0.092 ppb Rhodamine WT dye and analyzed without filtration. A linear regression analysis was used to correlate the expected fluorescence associated with turbidity and subtract that out leaving the response associated with the detection of dye. There was good (>90%) recovery of dye for turbidity concentrations less than 8.76 NTU. Recovery was poor at turbidity concentrations greater than 8.76 NTU.

Live Control Samples

King County prepared Rhodamine WT standards at concentrations of 92 ppb, 0.92 ppb and 0.092 ppb. The 0.92 standard was used for the live control sample (LCS) for the entire duration of the study. The LCS was measured several times each day that fluorescent measurements were made in the laboratory. The LCS was sealed with Para film and stored in a dark and dry environment at all other times. Over the four-month duration of the study, there was no degradation of the LCS.

Filtered vs. Unfiltered Samples

The dye standards were filtered through 0.45 micron filters to assess whether filtration captured any of the tracer. After several replicates of this test, a statistically significant effect on the 92 ppb standard was concluded. There was a statistically significant difference at the 0.92 ppb level, but the difference was less than the RDL of 0.04 ppb and thus considered negligible. There was no statistically significant difference on the 0.092 ppb standard.

Matrix Spike Recovery

King County conducted matrix spike recovery tests on random field samples to assess whether turbidity caused any interference or adsorption of dye. Tests were run at turbidity concentrations ranging from 1 to 55 NTU. There was close to 100 percent recovery in every sample. That is, there was no apparent masking of fluorescence or removal of the tracer by particles contributing to the turbidity.

Turbidity analysis was performed on samples with results above 0.040 ppb. A turbidity of less than 0.8 NTU was considered to contribute a negligible bias to the data. Samples with a turbidity above 0.8 NTU were considered to be potentially affected by turbidity and were therefore filtered and reanalyzed. Whatman puradisc 0.45 *um* polysulfone syringe filters were used for all samples requiring filtration. The procedures used were consistent with those developed and used in previous dye studies to deal with the affects of turbidity on low level analysis.

RESULTS

QA/QC

A large proportion of the sample and lab duplicate results were at or below the estimated RDL of 0.04 ppb, if not the MDL of 0.02 ppb. Greater variability in the method can be expected at these levels and this was reflected in high RPD calculations for a number of the duplicates.

Wind

Wind records from Paine Field are presented in Figure G-4 for the duration of each field study. Data are presented in GMT, which is 8 hours ahead of local standard time. Winds had a significant influence on the first two field studies. Although not truly reflected in the figure, a strong northwest wind occurred during the first study that forced suspension of boat operations on the day following the dye injection period. The strong winds were repeated in the second study, again just as the dye injection was being completed. This wind was from the south and is reflected in the wind figure. Winds during the third through fifth study were calm to moderate.

Shoreline Data

Study 1 – Browns Bay Shallow Site

The first dye injection began at 1655 on February 5 and ended at 0520 on February 6, 2001. The dye injection station was moored in the Browns Bay vicinity at a depth of 73 m. The diffuser was set at a shallow depth of 5 m at the top and 11 m at the bottom. 44.9 kg of Rhodamine WT dye was injected at a rate of 1.00 g/s over one semi-diurnal tide cycle.

The study was dominated by heavy northwest winds that set in immediately after the dye injection was complete. The strong winds forced suspension of the manual shoreline sampling on the second day of the study. It also raised turbidity in waters along the shorelines, which raised the background dye recordings to well above the RDL, which may have masked dye that had reached some of the stations. It was difficult to determine dye presence or absence at many of the shoreline stations due to the elevated background.

Time series graphs of dye concentration measured at selected shoreline sampling stations during Field Study No. 1 are presented from north to south in a series of Figures designated G-5A-E. The NOAA tide predictions for Edmonds and the period of dye injection are shown in each figure. The estimated background concentration is also indicated.

Very little dye was observed at concentrations above the MDL at shoreline stations north of the injection site during the study, which is illustrated by the Picnic Point station in Figure G-5A.

The only clear dye contact with shoreline stations was to the south (downwind) of the injection site. Trace concentrations on the order of 0.1 to 0.2 ppb were observed at the County Park (Fig. G-5B) and Ocean Avenue (Fig. G-5C) stations before the wind rose on the morning of Day 2. Similar concentrations were observed later in Day 2 at the Meadowdale (Fig. G-5D) and Edmonds (Fig. G-5E) autosampler locations, which were the only stations recording during the Day 2 windstorm. No significant dye concentrations were observed on subsequent days at any of the monitoring sites with the exception of the Edmonds station.

Observations: It is noteworthy that dye detected at the shoreline stations in Study No. 1 was observed only at low tides, almost without exception. This observation is illustrated most clearly in the Edmonds autosampler data (Fig. G-5E), but is also repeated at the other stations where dye was detected.

Study 2 – Point Wells Shallow Site

The second dye injection began at 0715 on March 12 and continued through 1938. The dye injection station was moored off Point Wells at a depth of 79 m. The diffuser was set at a depth of 5 m at the top and 11 m at the bottom. 50.2 kg of Rhodamine WT dye was injected at a rate of 1.13 g/s.

As with the first study, winds again affected the sampling program. Strong southerly winds set in at the conclusion of the dye injection system and continued into Day 2. Steady winds to 25 kn were observed at Paine Field with gusts to 40 kn. The strong winds and seas forced suspension of several of the manual sampling stations between 1730 on March 12 until 0700 on March 14.

Time series graphs of dye concentration measured at selected shoreline sampling stations during Field Study No. 2 are presented from north to south in a series of Figures designated G-6A-D. The NOAA tide predictions for Edmonds and the period of dye injection are shown in each figure. The estimated background concentration is also indicated.

Dye was detected only at shoreline stations north of the injection site. Figure G-6A shows the time series of measurements at the Ocean Avenue shoreline station. There were detected values slightly above the MDL at the conclusion of the dye injection and again the following afternoon. Winds were strong during both of these periods, so the significance of these measurements is suspect.

The Edmonds (Fig. G-6B) and Edwards Point (Fig. G-6C) autosamplers were online during windstorms on the last part of Day 1 and through Day 2. Both stations saw brief pulses of dye early on March 13 (approximately 6 to 8 hours after the dye injection ended), with concentrations approaching 0.2 ppb. These were the only clear dye observations during the entire study. There were detected values later in the windy day of March 13, but the concentrations were only nominally above the MDL of 0.04 ppb.

No dye was observed at concentrations above the MDL (0.04 ppb) at shoreline stations south of the injection site during the study. The time series of dye measurements at the North Richmond Beach

shoreline station is shown in Figure G-6D. This figure is typical of all of the data at the shoreline stations at Deer Creek, Point Wells, Richmond Beach Pump Station, South Richmond Beach, Boeing Creek, Spring Beach and Carkeek Park.

Field Fluorometry: During the first day of this study, the dye was tracked with the towed fluorometer moving primarily to the north of the release site (Fig G-6E). During day 3, dye was located primarily along the western side of the main basin (Fig G-6F). Figure G-6G shows the percentage of total detections at each depth and the maximum concentration observed at each depth. The peak concentration was observed slightly above the 5 meter release depth near the release site, with detections common to a depth of 20 meters. Observations on day 3 showed dye spread vertically to about 60 meters depth with the most frequent observations around 25 meters, but the greatest concentration near 10 meters.

Observations: A clear result of this study is that the wind-driven advection of dye discharged near the water surface in this study precluded transport to the southern shorelines. Wind-driven dye was observed briefly at the northern shoreline stations that remained online. It is unknown what would have been observed at either the northern or southern shorelines in the absence of the windstorm.

Study 3 – Browns Bay Deep Site

The third dye injection began at 0530 on May 7 and ended at 1800. The dye injection station was moored in the Browns Bay vicinity at a depth of 126 m. The diffuser was set at a depth of 22 m at the top and 28 m at the bottom, which were substantially deeper than the first two studies. 48.1 kg of Rhodamine WT dye was injected at a rate of 1.07 g/s for one semi-diurnal tide cycle.

Weather cooperated during this study and all stations were fully sampled for over four complete days. Winds were light with afternoon peaks to 12 kn, which is a typical wind pattern for Puget Sound.

Time series graphs of dye concentration measured at selected shoreline sampling stations during Field Study No. 3 are presented from north to south in a series of Figures designated G-7A-G. The NOAA tide predictions for Edmonds and the period of dye injection are shown in each figure. The estimated background concentration is also indicated.

All of the shoreline stations north of the injection site observed dye, while none was observed at stations to the south of Browns Bay. Peak concentrations reached approximately 0.4 ppb, which was the highest of the four studies. The peak concentrations generally occurred near the end of the dye injection and late morning of Day 2. Trace concentrations were observed on Day 3.

Figure G-7A shows the time series of dye concentrations measured at the Picnic Point shoreline station, which was the most northern sampling site. Dye was observed persistently during Days 2 and 3 of the study at concentrations up to 0.15 ppb.

Figures G-7B and G-7C show the time series of dye concentrations measured at the Norma Beach and Meadowdale Beach shoreline stations. Similar patterns of detected concentrations were observed at these stations, with higher concentrations of up to 0.25 ppb. Earlier detections (near the end of the dye injection period) were also observed at these stations than the Picnic Point station.

Figure G-7D shows the time series of dye concentrations measured at the Meadowdale Marina Autosampler. Figure G-7E shows a similar time series for the Browns Bay station about _ mi south of the marina. The highest dye concentrations of up to 0.4 ppb were observed at these two stations near the conclusion of the dye injection period on Day 1.

Figure G-7F shows the time series of dye concentrations measured at the South Browns Bay shoreline station. Peak concentrations of approximately 0.13 ppb were observed early on Day 2. This monitoring station was the most southerly site where dye was observed. Figure G-7G shows the time series at the

Edmonds autosampler, indicating the persistent background concentrations that prevailed at the southern station.

Field Fluorometry: During the three days of this study, the dye was tracked with the towed fluorometer. On the first day, the dye was observed slightly to the north and both onshore and offshore of the release site (Fig G-7H). During the second and third days, dye was observed to the north of the release site, through Possession Sound almost to Gedney Island (Figures G-7I and G-7J). Figure G-7K shows that the greatest dye concentrations remained in the 15 to 30 meter depth range during these three days. The near surface concentrations on day 2 are similar to those observed along the shoreline.

Observations: Clear and persistent dye presence was measured onshore and north of the injection site late on Day 1 and through Day 2, beginning near the end of the dye injection period. The origin of the dye cloud measured on the shoreline was evident from measurements made with the towed fluorometer. Prior to observing dye on the shoreline, the towed fluorometer detected and tracked dye discharged late in the ebb tide and at the low water stand (mid- to late-morning of Day 1), which was advected toward shore during the ensuing flood tide. The dye cloud discharged during the morning ebb was tracked shoreward until it reached the nearby shoreline monitoring stations at the following high tide. Therefore, the peak concentrations measured at the Meadowdale Marina and Beach Park were estimated to be between 6 and 10 hours old (*i.e.* age of the dye cloud since time of discharge). The secondary peaks observed at Meadowdale Beach, Norma Beach and Picnic Point occurred on the order of 24 hours after discharge.

Study 4 – Point Wells Deep Site

The fourth dye injection occurred between 0450 and 1840 on June 5, 2001 during a large ebb and flood cycle. The dye injection station was moored off Point Wells at a depth of 190 m. The diffuser was set at a depth of 22 m at the top and 28 m at the bottom, the same as Study 3. 51.1 kg of Rhodamine WT dye was injected at a rate of 1.03 g/s.

All of the shoreline stations were fully sampled for 3.5 days according to the study plan. Winds were light with typical afternoon peaks to 12 kn.

Time series graphs of dye concentration measured at selected shoreline sampling stations during Field Study No. 4 are presented from north to south in a series of Figures designated G-8A-G. The NOAA tide predictions for Edmonds and the period of dye injection are shown in each figure. The estimated background concentration is also indicated.

Shoreline stations far north of the injection site did not experience any measurable dye. The time series of dye measurements at the Meadowdale Marina and Browns Bay stations are shown in Figures G-8A and G-8B. Slight peaks in fluorescence were observed around high tides on Days 2 and 3 of the study. However, these slightly elevated concentrations were at or below the RDL of 0.04 ppb. While it is likely that trace dye was measured at these sites, we can not conclude that these peaks were associated with the dye release.

The only stations that consistently observed dye during this study were the Edmonds and Edwards Point autosamplers and Deer Creek shoreline, as shown in the time series Figures G-8C through G-8E. Peak concentrations approached 0.1 ppb at Edmonds and occurred near the end of the dye injection period. Lower concentrations with longer durations of dye presence were observed on Days 2 and 3 at this station. The Edwards Point and Deer Creek data were similar to the Edmonds station in concentration, timing and duration, except did not experience the brief peak near the end of the dye injection on Day 1.

All of the southern monitoring station data were generally below the RDL. The exceptions occurred at the Richmond Beach Pump Station and North Richmond Beach shoreline stations, which are shown in Figures G-8F and G-8G. Each station experienced a single spike of dye concurrently late in the ebb tide

at a concentration of approximately 0.1 ppb. All other measurements at these stations and the other southern stations remained below the RDL.

Field Fluorometry: During the two days of this study, the dye was tracked with the towed fluorometer moving primarily to the north of the release site (Fig G-8H, Fig G-8I). No coherent patch of dye was observed on the third day (Figure G-8J), but dye was observed at scattered locations from Pt Wells to Admiralty Inlet. Figure G-8K shows the majority of detections occurred near 20 meters depth, as did the maximum concentrations. Detections on the third day were scattered between the surface and 20 meters depth, with low concentrations.

Observations: Similar to the Browns Bay deep injection study in May, the Point Wells study also had a dye cloud that persisted along the adjacent and northern shoreline for about two days. Like the Browns Bay study, the towed fluorometer was able to track the dye cloud from the point of discharge to the vicinity of the shoreline sampling stations where it was observed 6 to 10 hours after discharge. In comparison to the Browns Bay study, the length of shoreline impacted by the dye cloud was smaller, and the observed concentrations were on the order of 25 percent for the peaks (0.4 ppb Browns Bay, 0.1 ppb this study) and 50 percent for the secondary events (0.15 ppb Browns Bay, 0.07 ppb this study).

Study 5 – Edwards Point Deep Site

The fifth dye injection occurred from 1440 February 4 through 0300 February 5, 2002 during a minor flood and ebb cycle. The dye injection station was moored off Edwards Point at a depth of 171 m. The diffuser was set at a depth of 55 m at the top and 61 m at the bottom, which was substantially deeper than the previous studies. 95.5 kg of Rhodamine WT dye was injected at a rate of 2.15 g/s.

All of the shoreline stations were fully sampled for up to four days according to the study plan. Winds were calm at night with typical afternoon peaks to 10 kn.

Time series graphs of dye concentration measured at selected shoreline sampling stations during Field Study No. 5 are presented from north to south in a series of Figures designated G-9A-D. The NOAA tide predictions for Edmonds and the period of dye injection are shown in each figure. The estimated background concentration is also indicated on each graph.

Only four graphs are presented, but the results were the same for all nine stations that were sampled during this study. None of the shoreline field samples exceeded the RDL of 0.04 ppb during this study. Over 95 percent of the results were below the MDL of 0.02 ppb. Therefore, there is no indication of any shoreline contact of dye injected at the Edwards Point deep station.

There is an apparent pattern of the highest recorded concentrations coincident with low tide (see Figs. G-9B and G-9C). However, these observations could be random, an indication of very low dye concentrations, or some tidally-related variation in background fluorescence. No conclusions are possible since even the peak concentrations were below the RDL.

Field Fluorometry: Dye was observed moving northward from release site during the afternoon of February 4 (Fig G-9E). Observations on February 5 and 6 (Fig G-9F) and FigG-9G) found dye to the north of the release site, but south of Whidbey shoal. No dye was detected on February 7 (Fig G-9H). Figure G-9I illustrates the vertical distribution of the dye, which was found between 25 and 100 meters depth.

Observations: There is no indication of any shoreline contact of dye injected at the Edwards Point deep station.

Estimated Effluent Concentration at Shoreline Stations

The shoreline concentration data allow assessment of the long-term accumulation of effluent for a simulated discharge. The methods of Hubbard and Stamper (1972) have been used to assess long-term accumulation of effluent at the shoreline stations for a 54 mgd (2.4 m^3/s) discharge. This method uses the principal of superposition to establish a quasi-steady effluent concentration for each monitoring site. Since the duration of each dye injection was one semi-diurnal tide cycle (approximately 12.4 hours), the peak measured concentrations of each successive semi-diurnal period are added. The sum of these peaks is the quasi-steady peak effluent concentration for the shoreline stations.

The modeling for a 54 mgd discharge is conducted two ways. The first model provides conservative (*i.e.* worst-case) estimates of effluent concentration using the principal of superposition without modification. This method estimates the minimum dilution factor at the shoreline. The first model neglects the rapid initial mixing that will occur for every outfall alternative. Therefore, the second modeling technique still uses the principal of superposition, but adjusts each semi-diurnal peak to account for the high initial dilution factor.

The prototype 54 mgd discharge will experience rapid mixing due to the effluent buoyancy in sea water, with initial dilution factors on the order of 200:1. The plume width following initial dilution will also be on the order of 100 to 500 feet at the neutrally-buoyant "trapping" depth. The dye releases simulated a "point source" discharge, which was initially only about 10 feet wide in the ambient flow. A 10-ft-wide plume will disperse differently than a 100- to 500-foot-wide plume. The second method adjusts each measured shoreline concentration by the time-weighted difference in farfield mixing due to initial plume dimensions. The adjusted farfield dilution is factored with the projected initial dilution to assess the shoreline dilution factor. The second method is intended to be a more realistic prediction of shoreline concentrations than the first method.

The predictions of both modeling methods must be considered first-order estimates, or order-of-magnitude estimates. Precision calculations are not possible due to the low dye concentrations measured compared to background, and the broad modeling assumptions in the second modeling method.

The results are shown in Table G-2 for each dye study. Shoreline contact is quantified as both dilution factor and effluent concentration. Effluent concentration is the volumetric fraction (or percentage) of a sample consisting of effluent. Dilution factor is the inverse of effluent concentration. Predictions are provided for all shoreline stations that had measured concentrations above the RDL of 0.04 ppb. Predictions are also shown for all of the stations that had no detected effluent, using the RDL of 0.04 ppb in the calculations. Values calculated for non-detect stations are noted by "greater than" and "less than" signs.

Conclusions

The shoreline effluent concentration cannot be estimated from the first two dye release studies because of the winds that occurred on Day 2 of both. The weather conditions forced cessation of the beach sampling during critical periods of the study. The higher turbidity also affected the measurement of beach samples when the study resumed. No conjecture is offered of the impact the winds may have had on transporting dye out of the study area, or what would have prevailed had the winds not occurred.

The first four studies conclusively detected dye at selected shoreline stations. None of the measured shoreline concentrations exceeded an order of magnitude above the RDL. The highest measured concentrations occurred during the Browns Bay injections, by a factor of two to four over the Point Wells site. The length of shoreline impacted was greater in the Browns Bay studies than the Point Wells studies.

There was no shoreline contact of dye from the fifth study, despite a doubling of the dye dosage. This injection was much deeper than the previous studies, at a depth of 55 to 61 m. This injection depth range corresponds to the effluent plume trapping depth for a deep outfall alternative.

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Wilson, J. *et al.* 1986. Fluorometric procedures for dye tracing, U.S. Geol. Survey, Washington D.C.

Figure G-1. **Dye injection schematic**

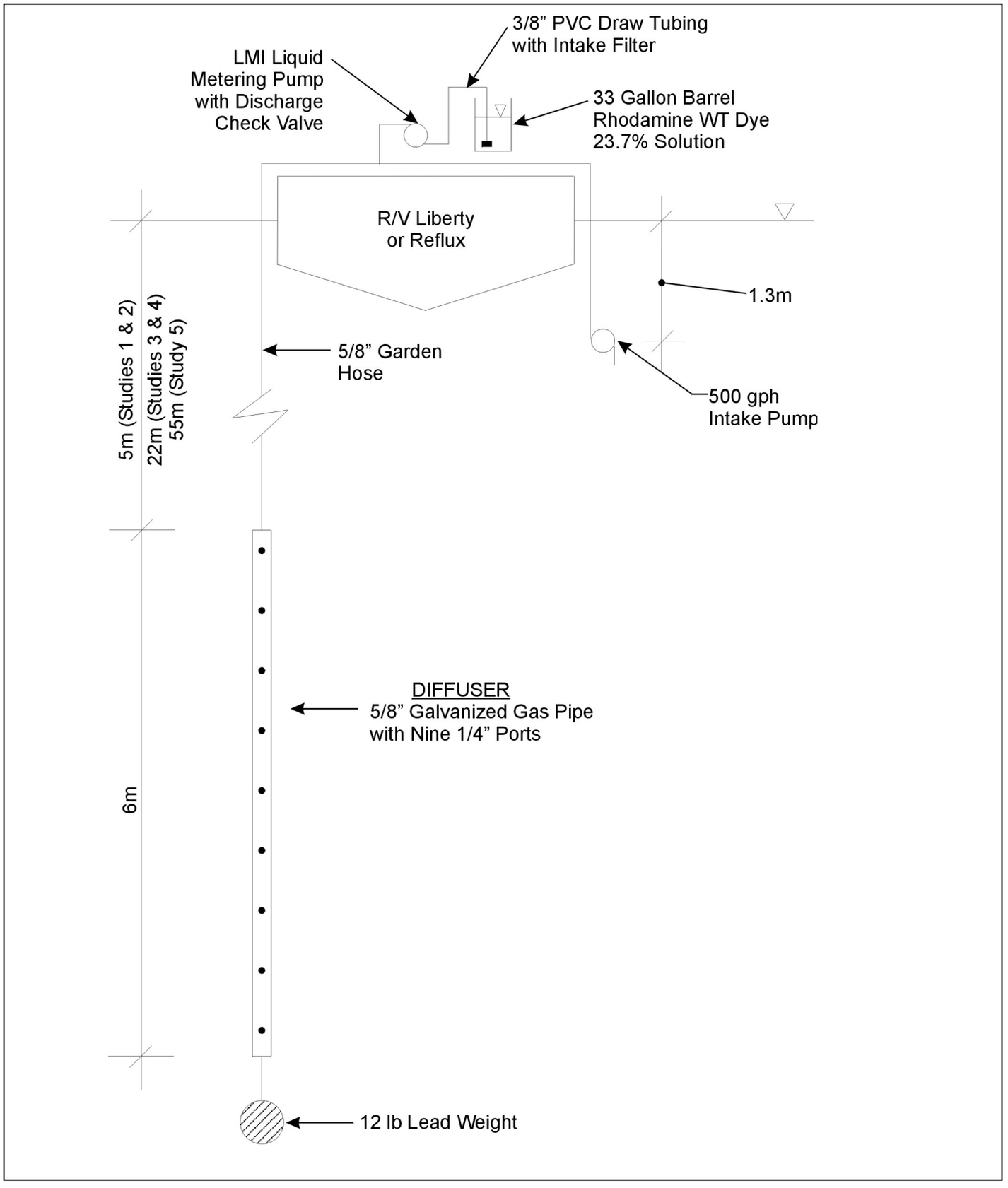


Figure G-2. **Shoreline dye sampling locations**

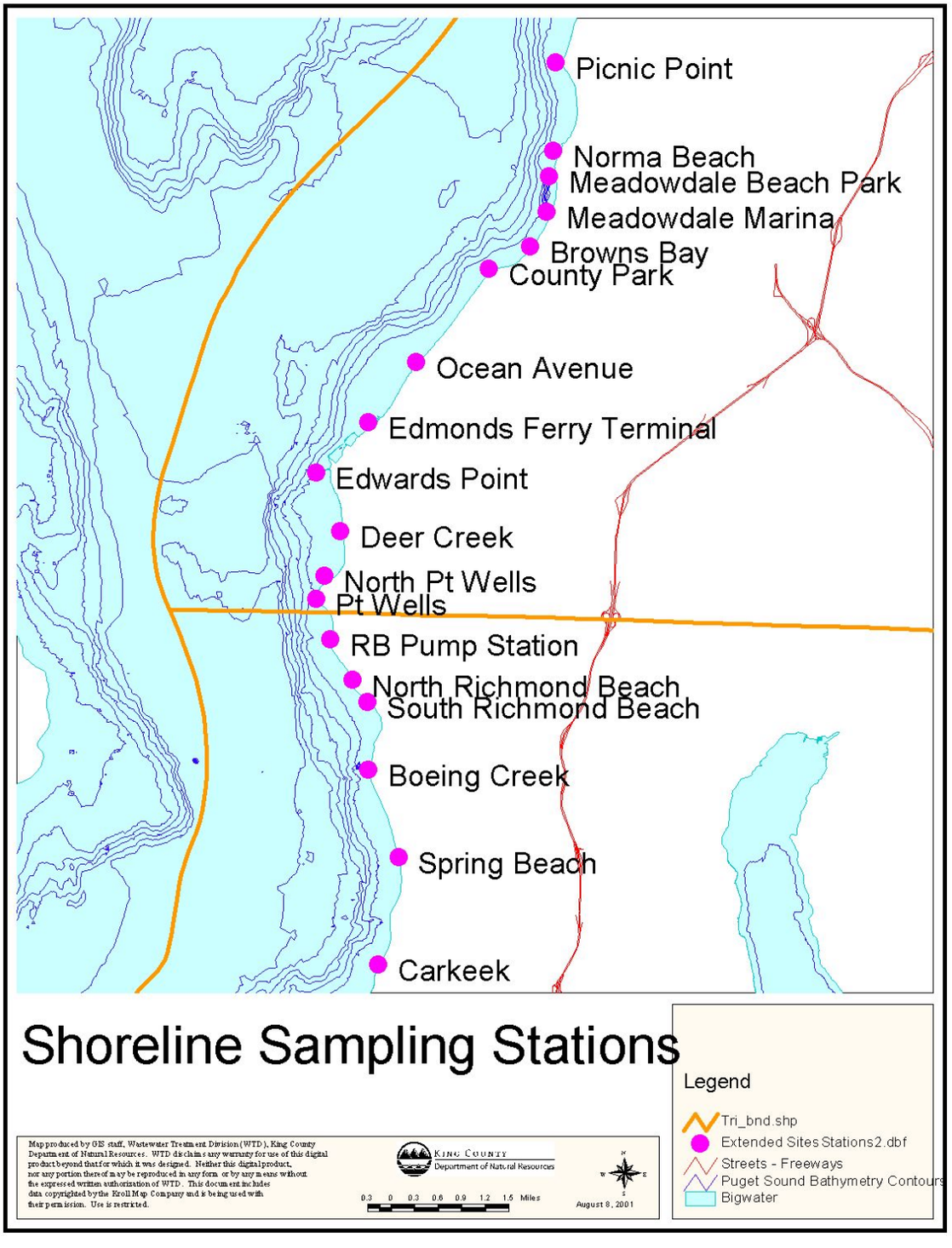
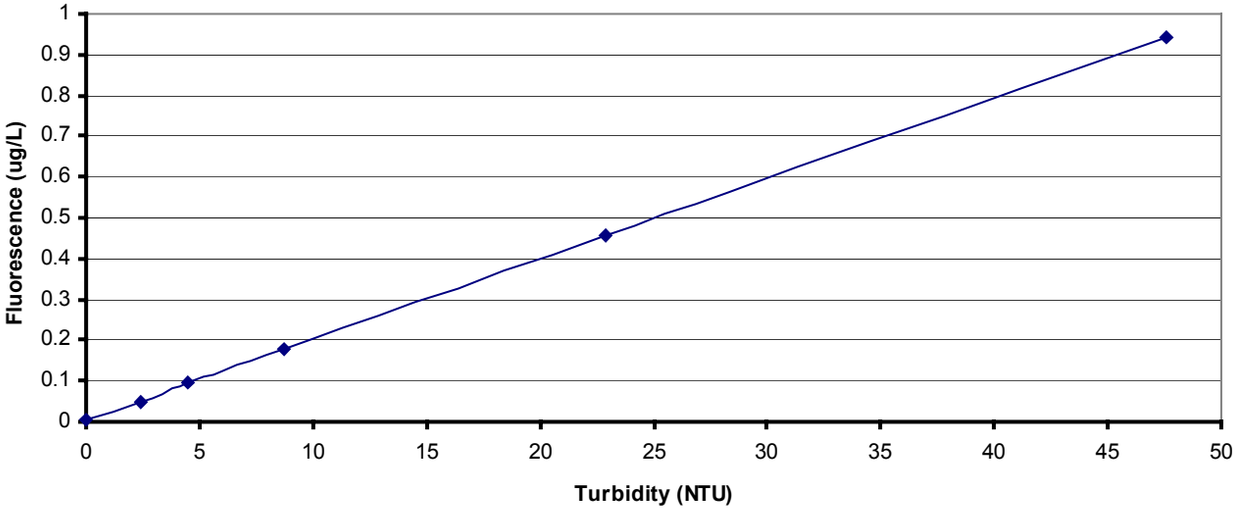


Figure G-3. **Turbidity effect on fluorescence**



Graph showing the dye concentration equivalent to the fluorescence measured in a blank laboratory sample with known turbidity values. This correlation was used to correct fluorescence readings in field samples that had a high level of turbidity.

Figure G-4. **Wind speeds during dye studies**

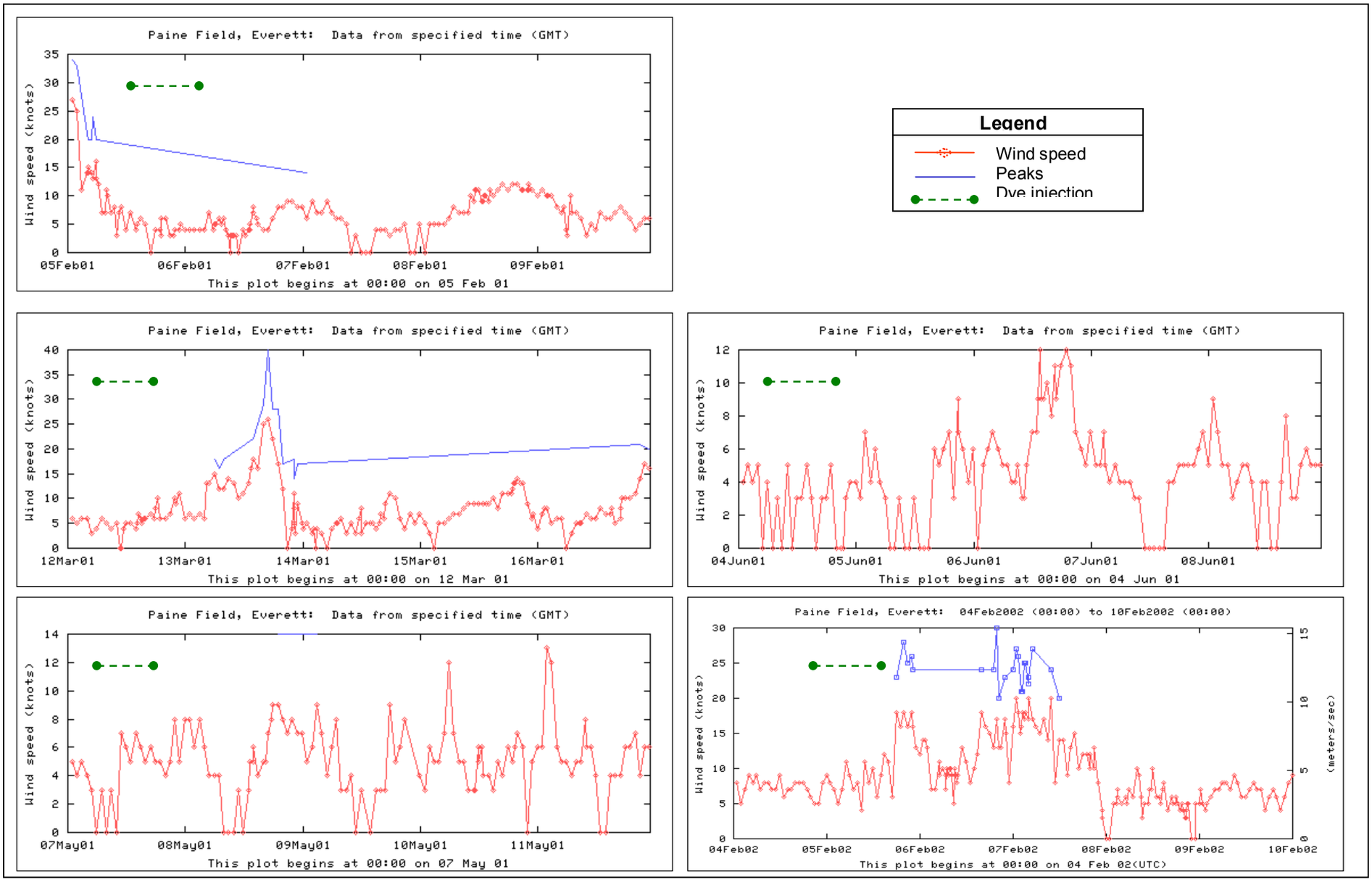


Figure G-5A. **Dye Study 1, Picnic Point Station**

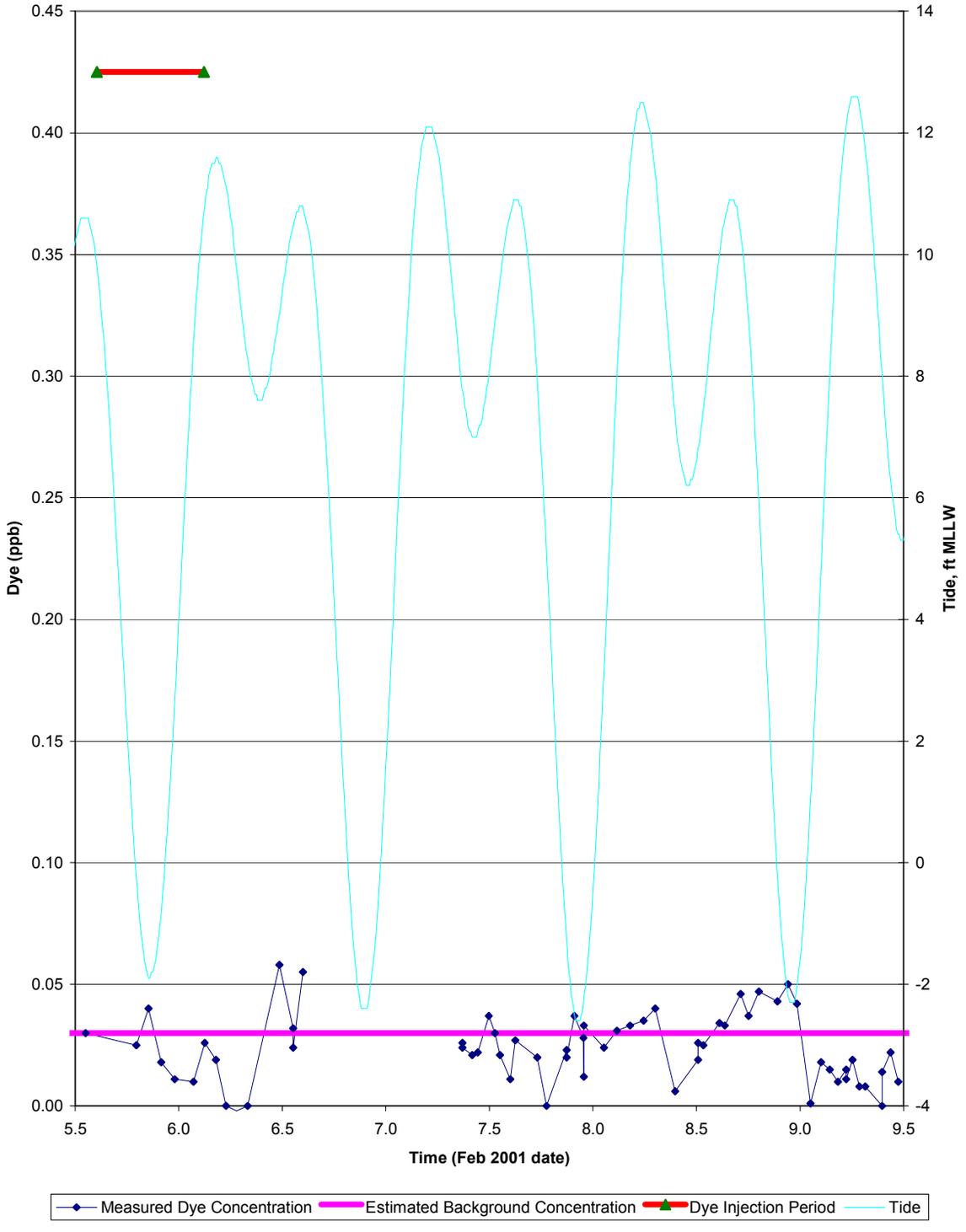


Figure G-5B. **Dye Study 1, County Park Station**

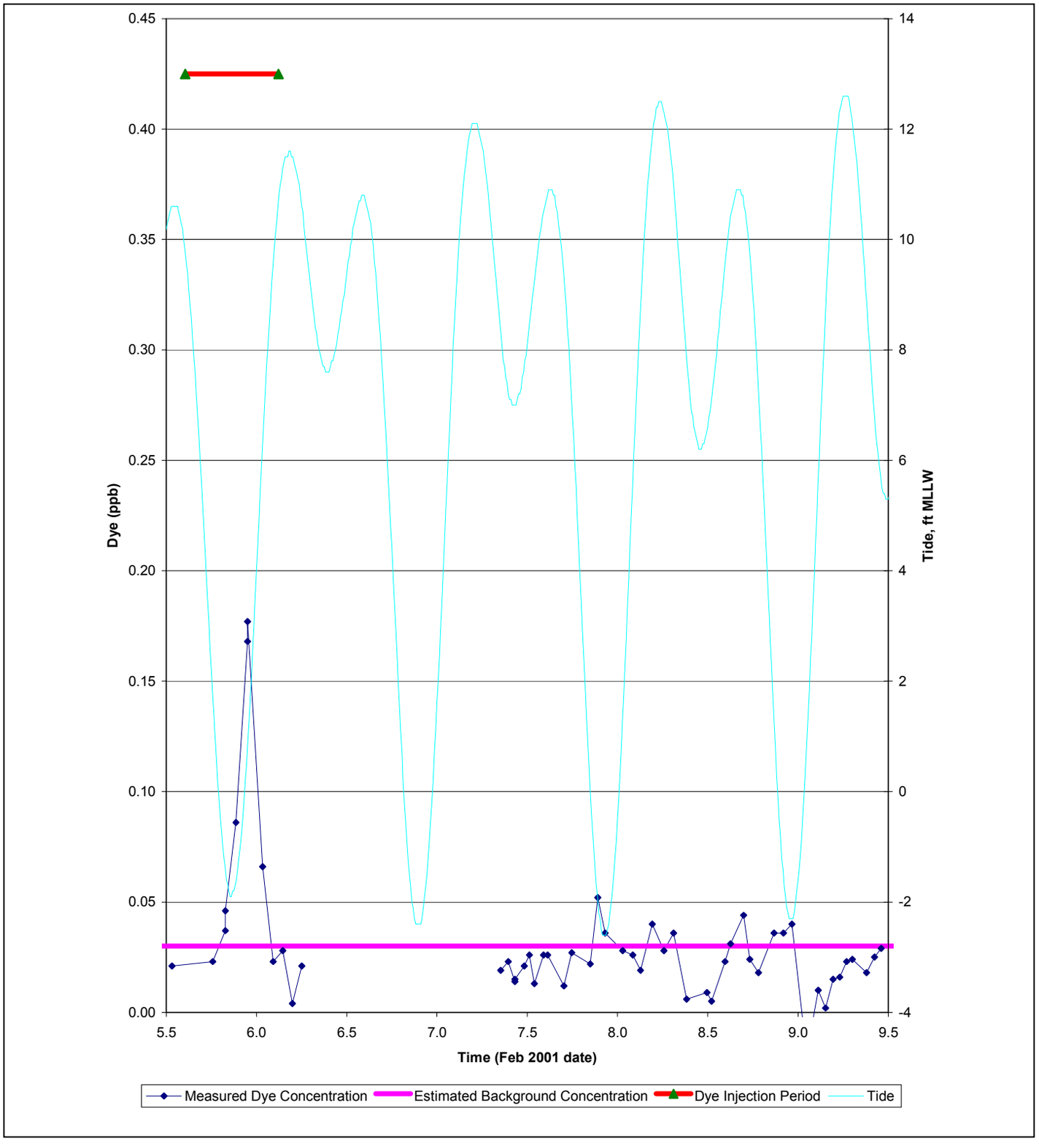


Figure G-5C. **Dye Study 1, Ocean Avenue Station**

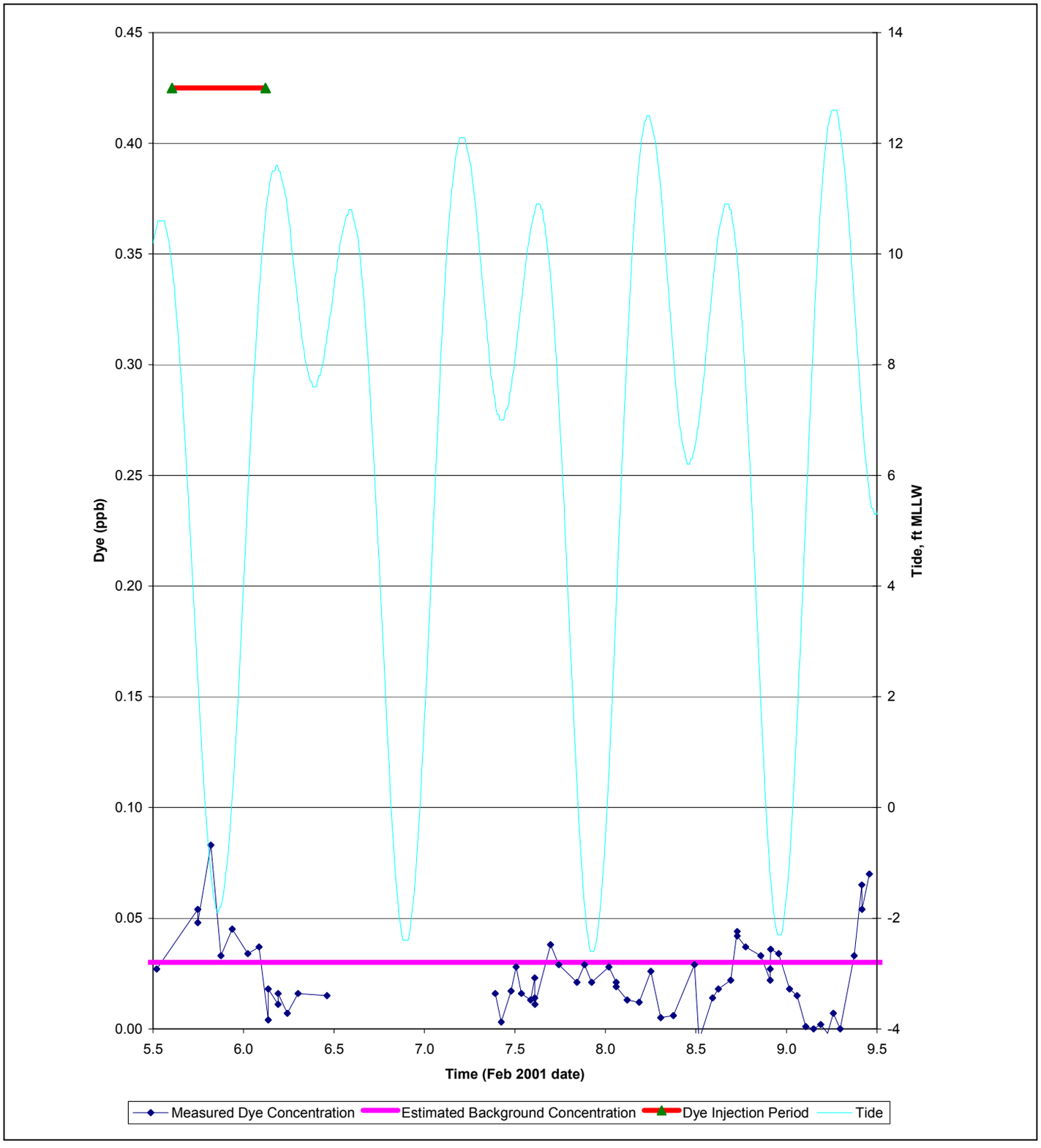


Figure G-5C. **Dye Study 1, Meadowdale Marina Autosampler**

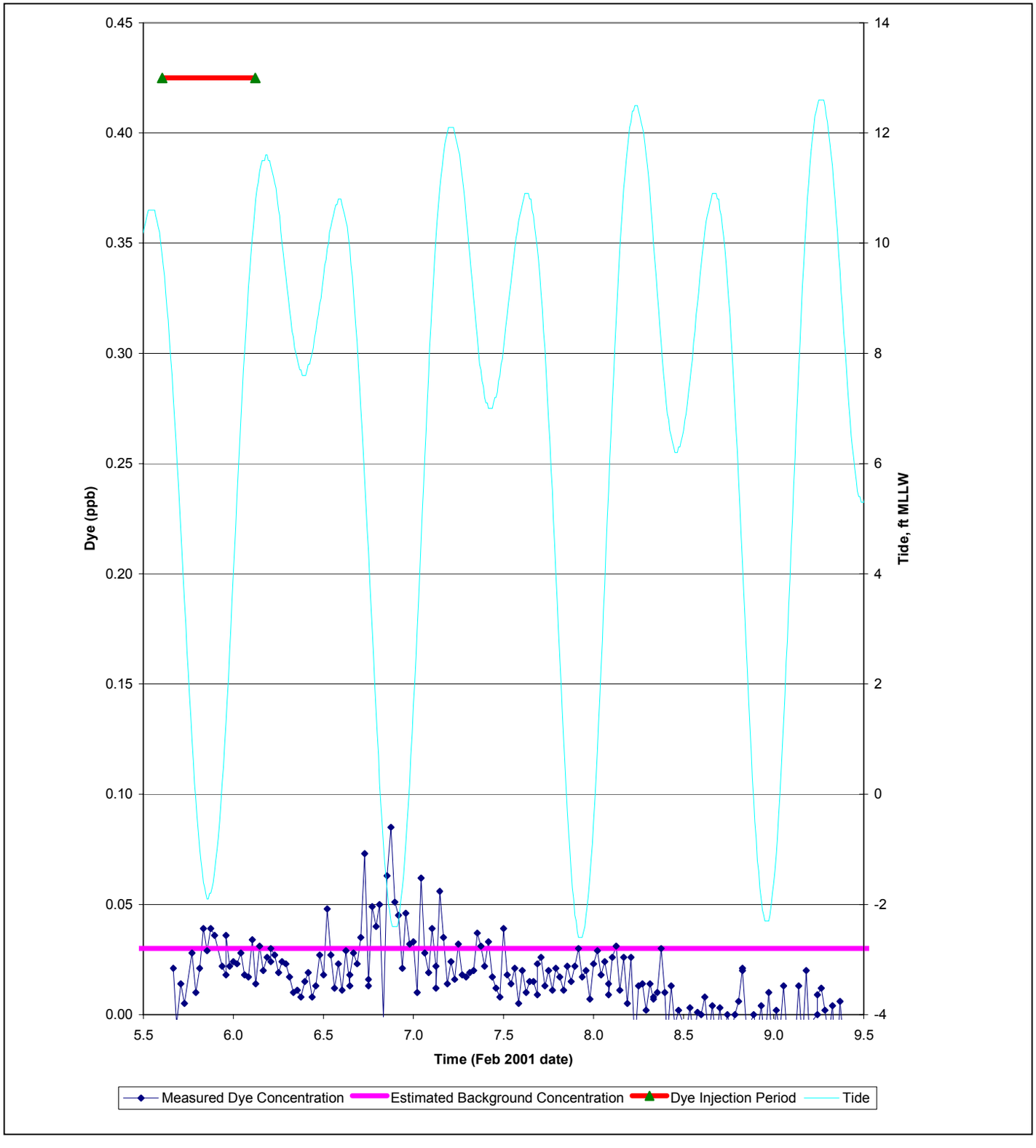


Figure G-5E. **Dye Study 1, Edmonds Autosampler**

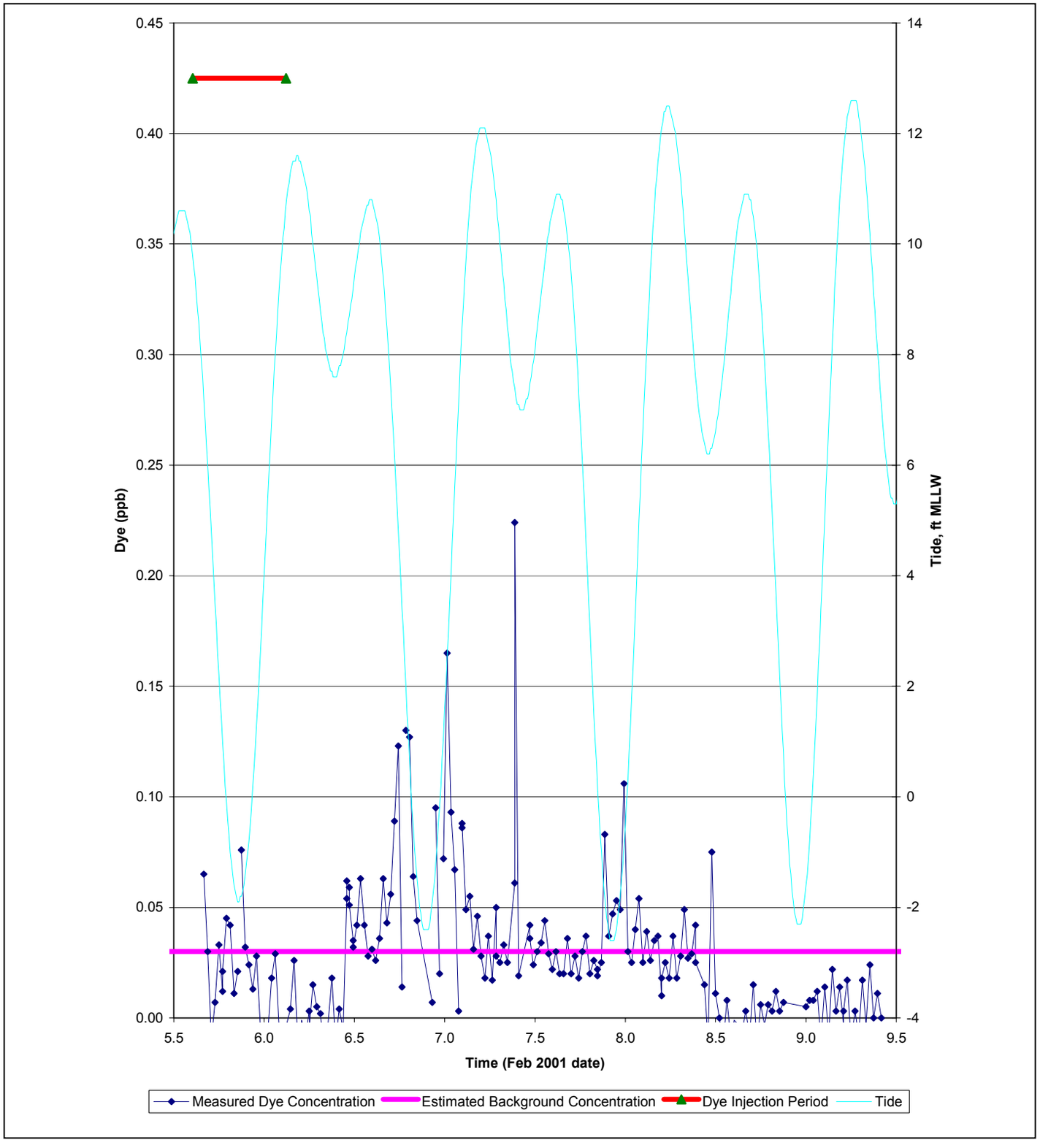


Figure G-6A. **Dye Study 2, Ocean Avenue Station**

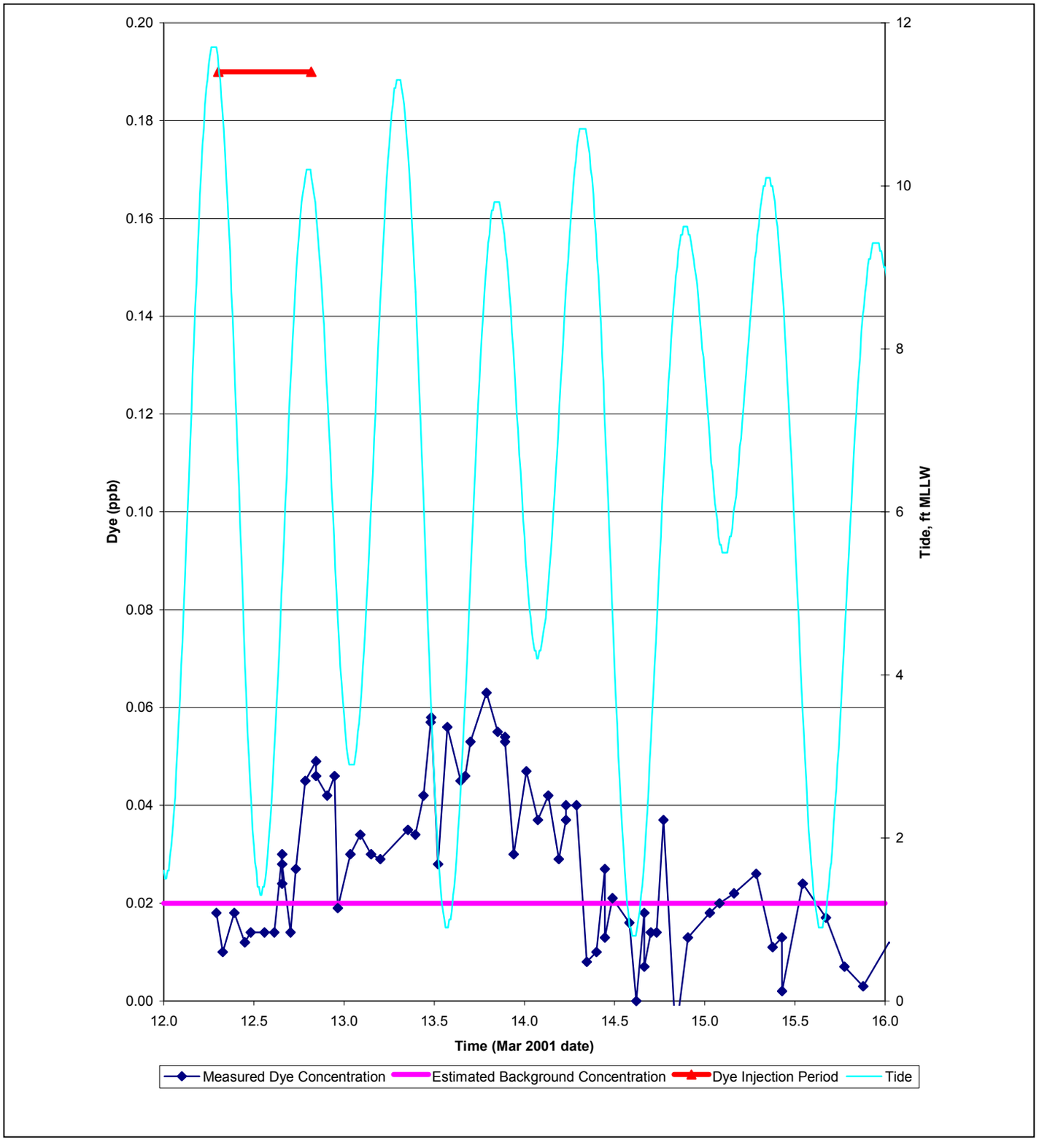


Figure G-6B. **Dye Study 2, Edmonds Autosampler**

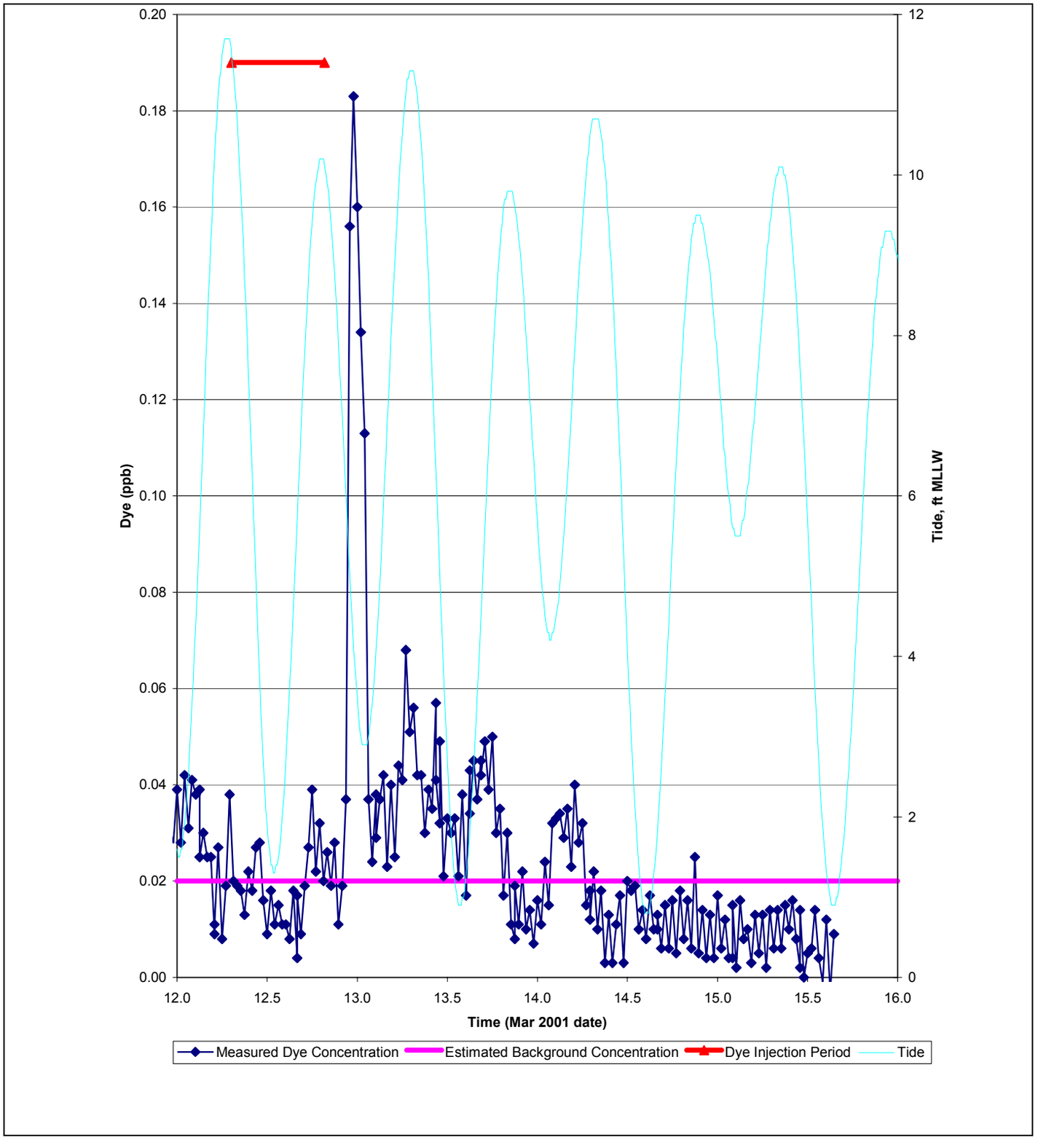


Figure G-6C. **Dye Study 2, Edwards Point Autosampler**

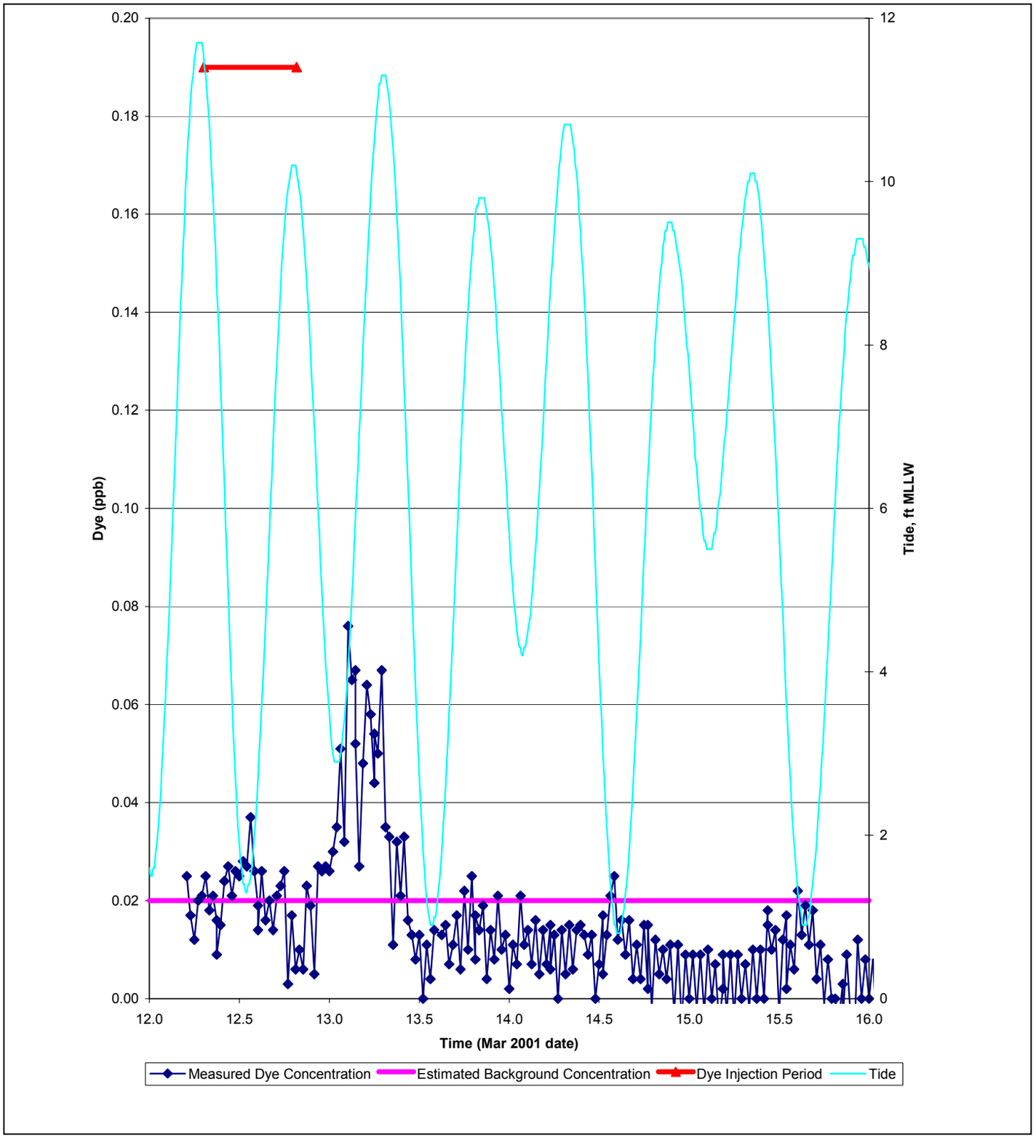


Figure G-6D. **Dye Study 2, North Richmond Beach Station**

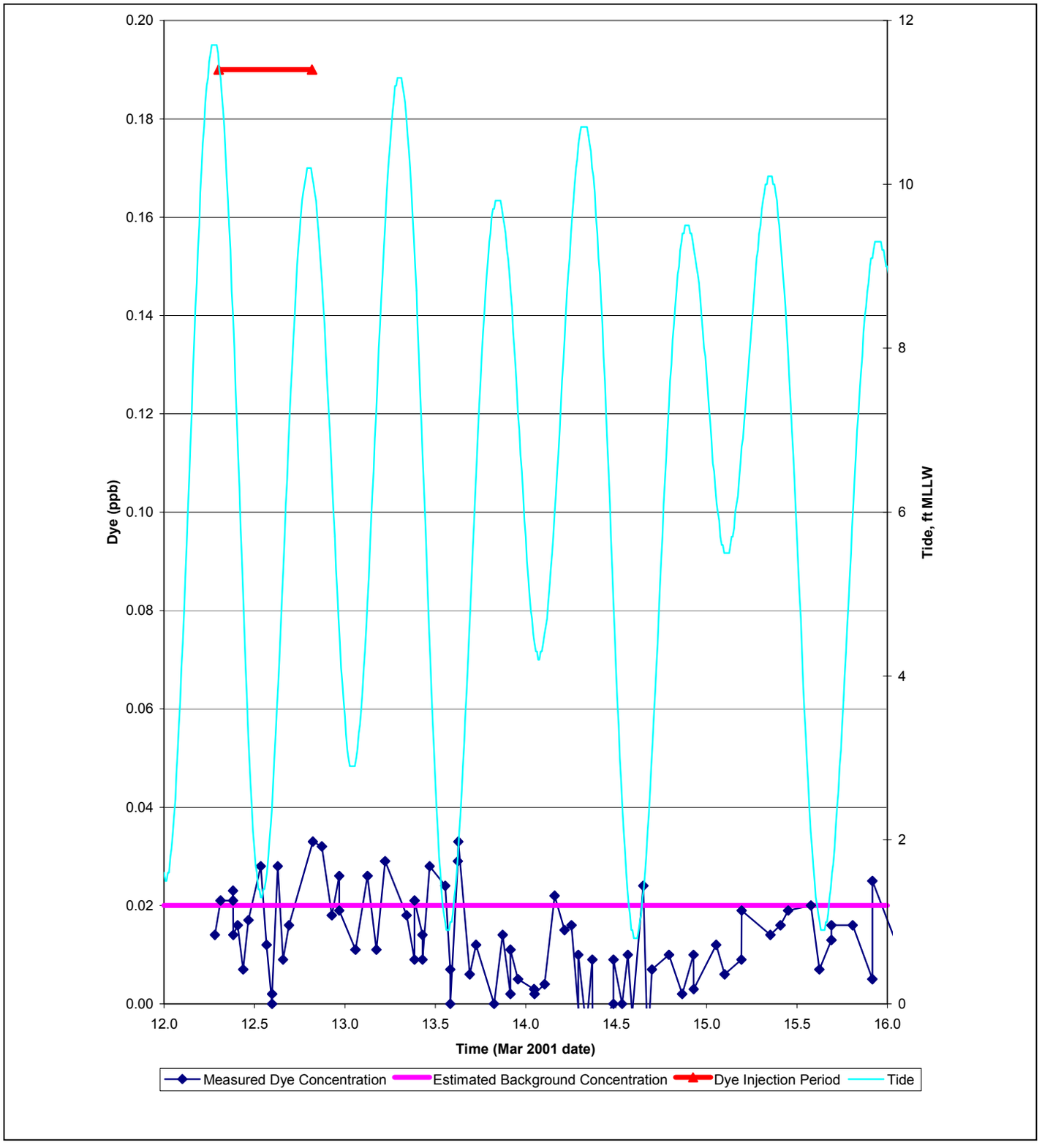
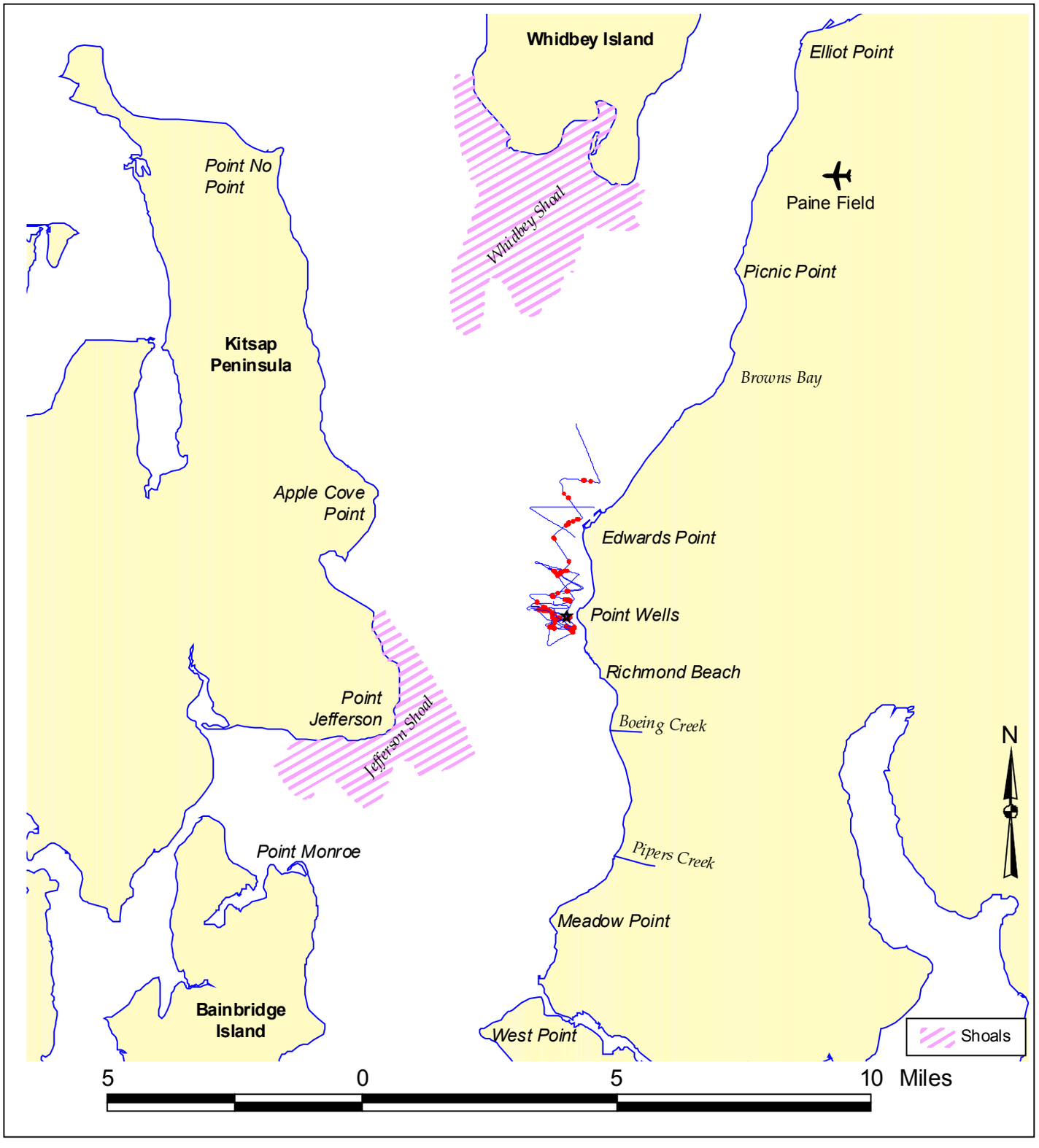
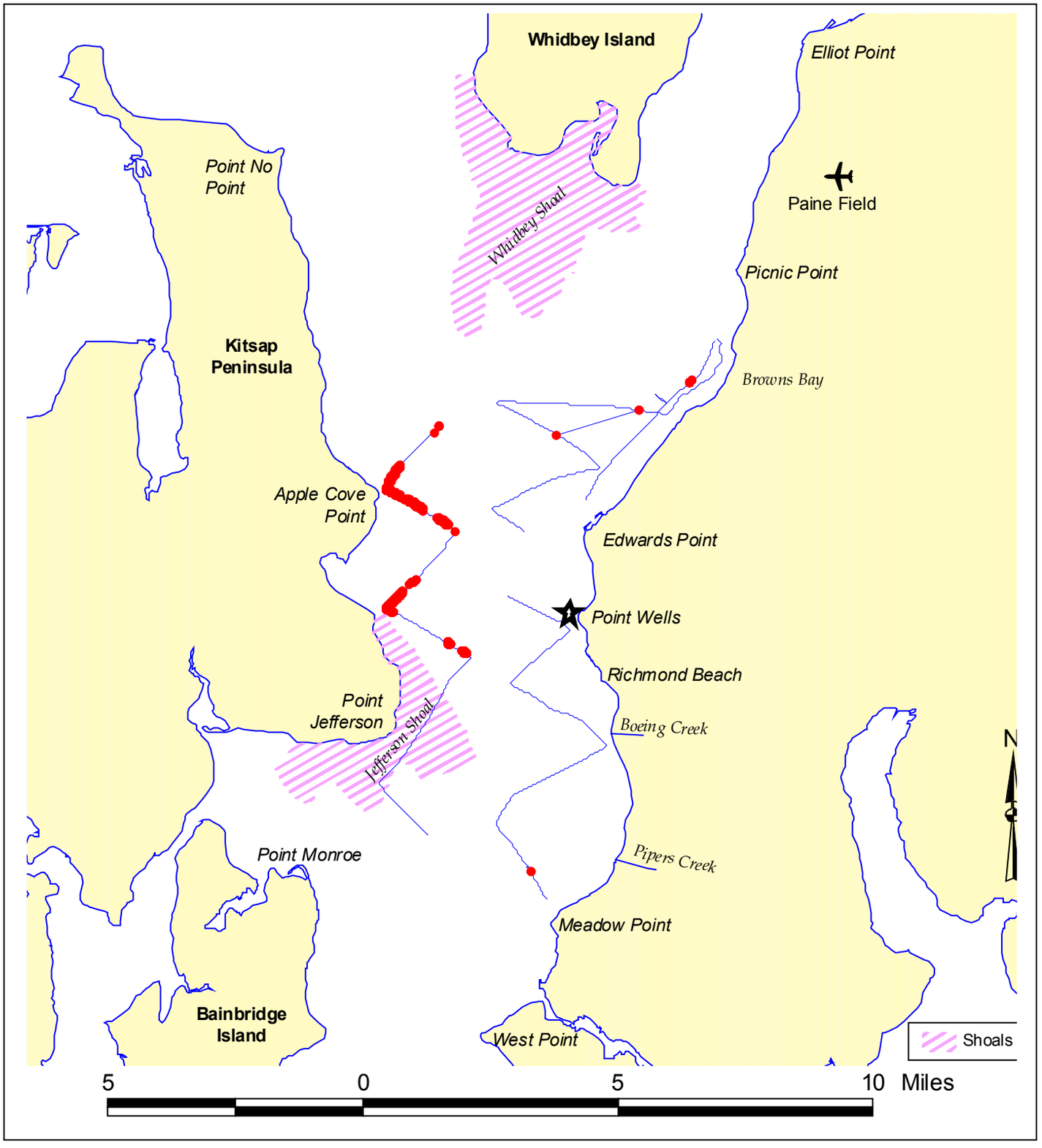


Figure G-6E. **Dye Study 2, Day 1 Towed Fluorometer Track**



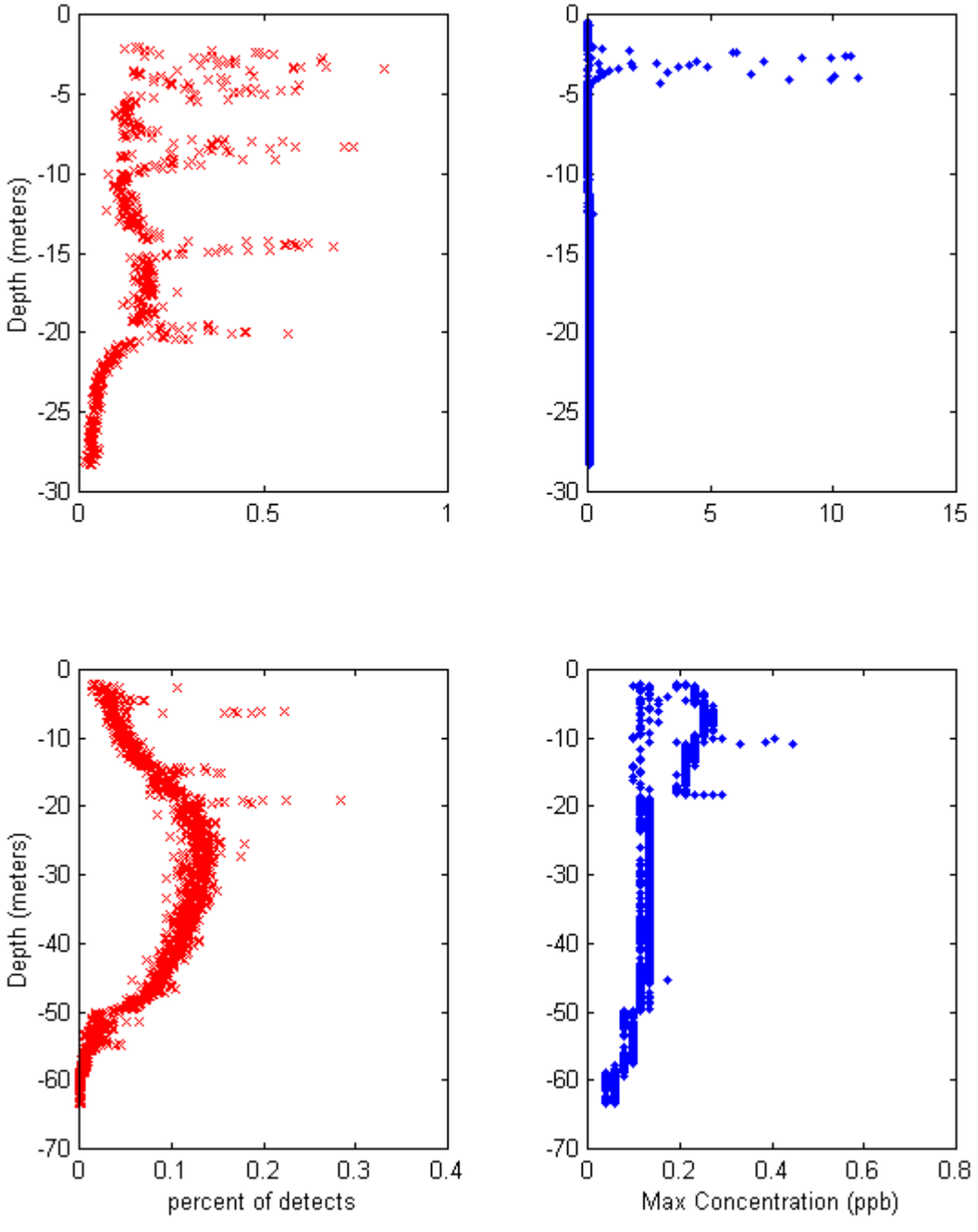
Horizontal path of towed fluorometer during day 1 (March 5, 2001) shown as solid blue line. Red dots represent locations with measured fluorescence levels indicating dye concentrations greater than 1 ppb. Black star indicates the dye release location.

Figure G-6F. **Dye Study 2, Day 3 Towed Fluorometer Track**



Horizontal path of towed fluorometer during day 3 (March 7, 2001) shown as solid blue line. Red dots represent locations with measured fluorescence levels indicating dye concentrations greater than 0.1 ppb. Black star indicates the dye release location.

Figure G-6G. **Dye Study 2, Depth Profile of Dye Observations**



Vertical distribution of dye observations. Left panel shows, of the samples above the detection limit, the percentage that occurred at each depth (total of all depths is 100%). Right panel shows the maximum concentration observed at each depth. Top panels are observations from day 1 (March 5, 2001), bottom panels from day 3 (March 7, 2001).

Figure G-7A. **Dye Study 3, Picnic Point Station**

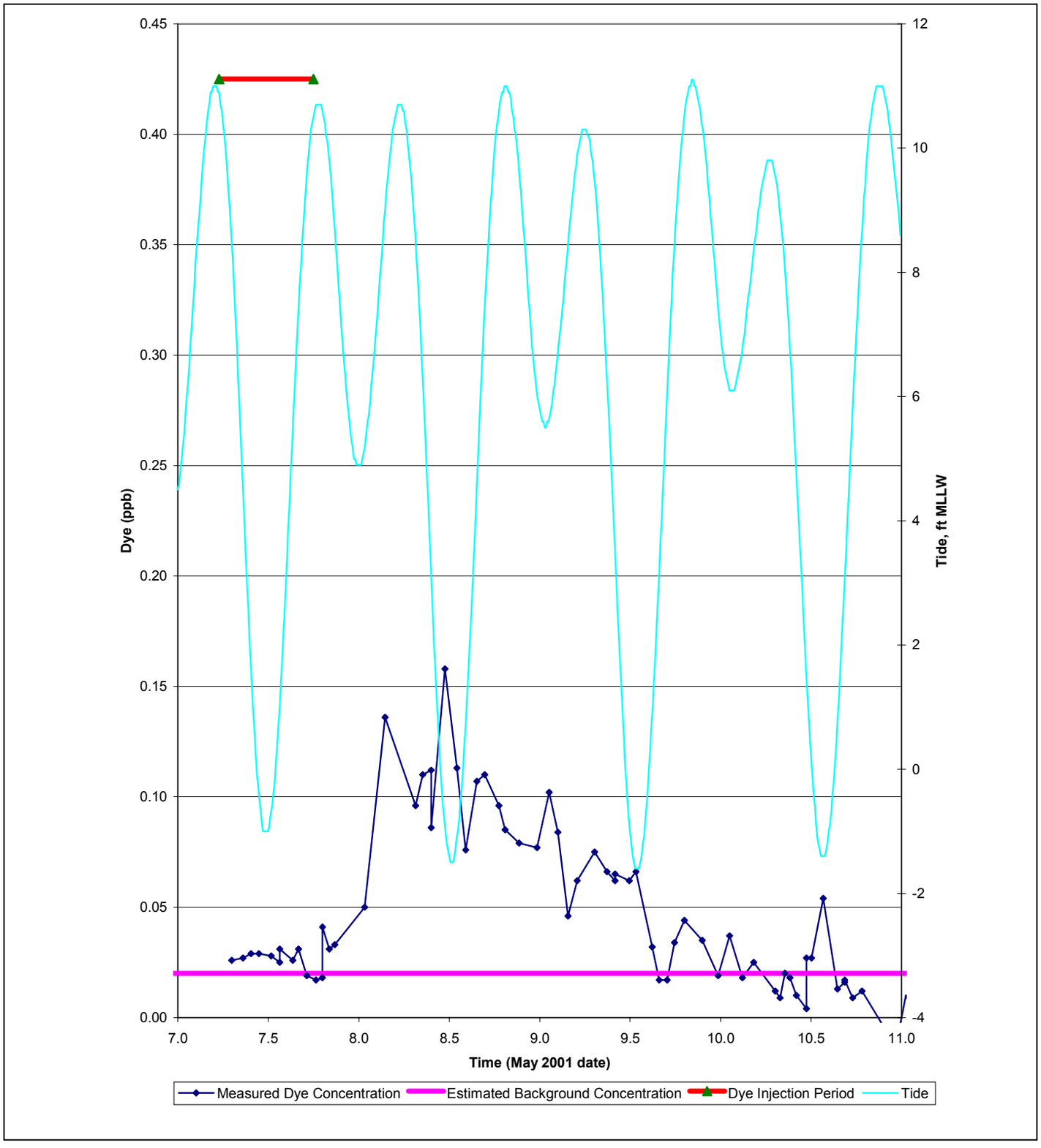


Figure G-7B. **Dye Study 3, Norma Beach Station**

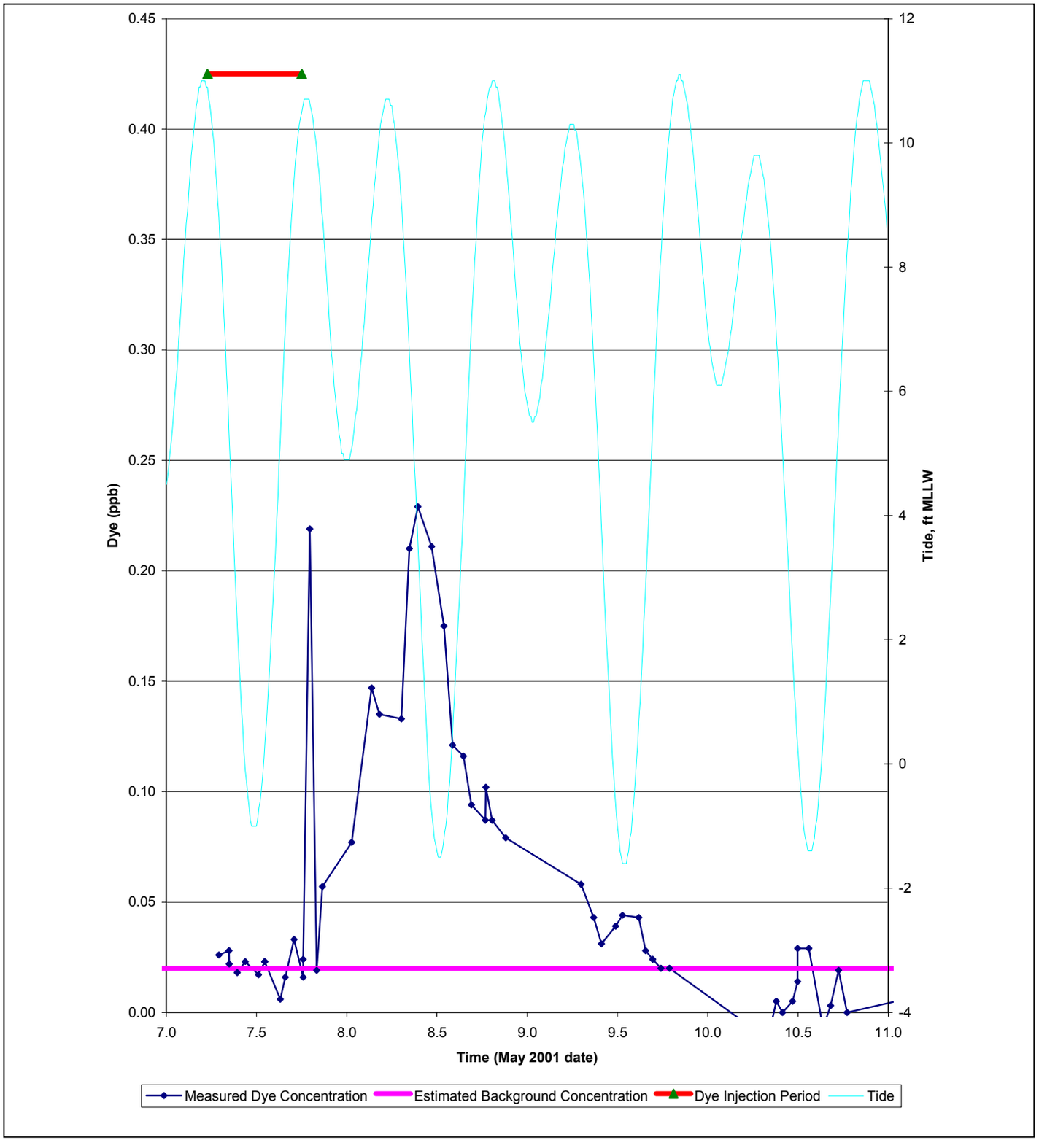


Figure G-7C. **Dye Study 3, Meadowdale Beach Station**

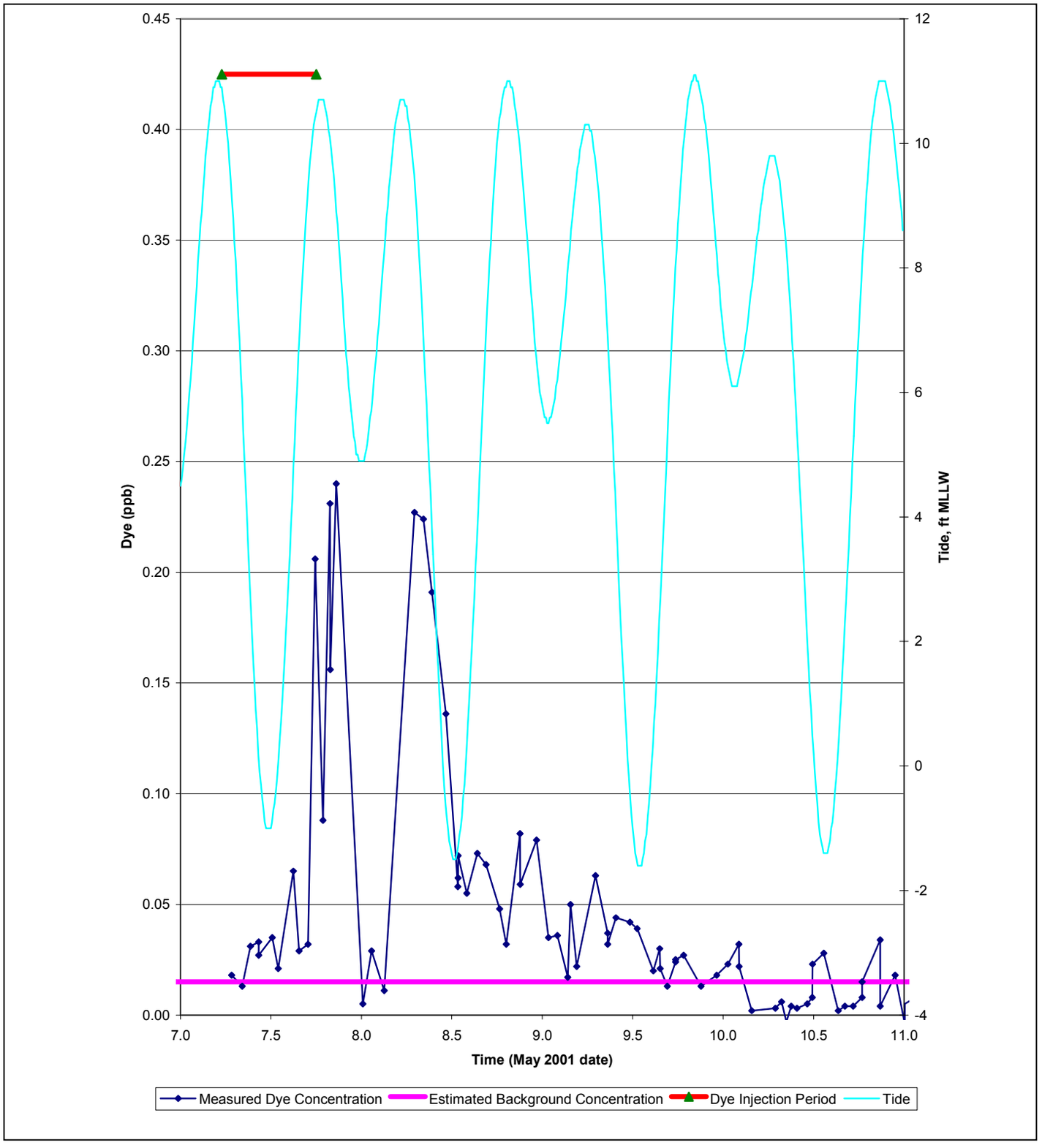


Figure G-7D. **Dye Study 3, Meadowdale Marina Autosampler**

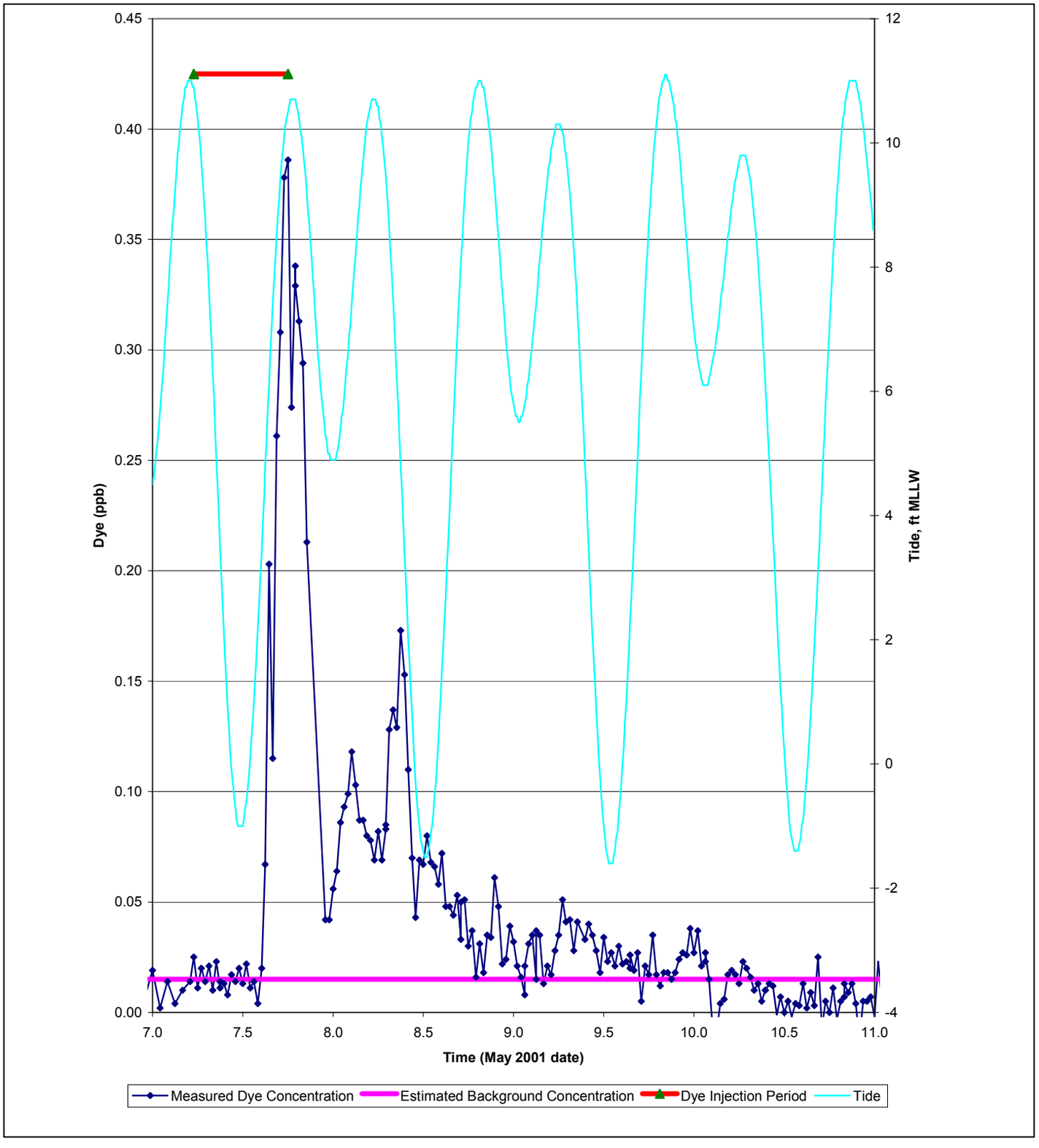


Figure G-7E. **Dye Study 3, Browns Bay Station**

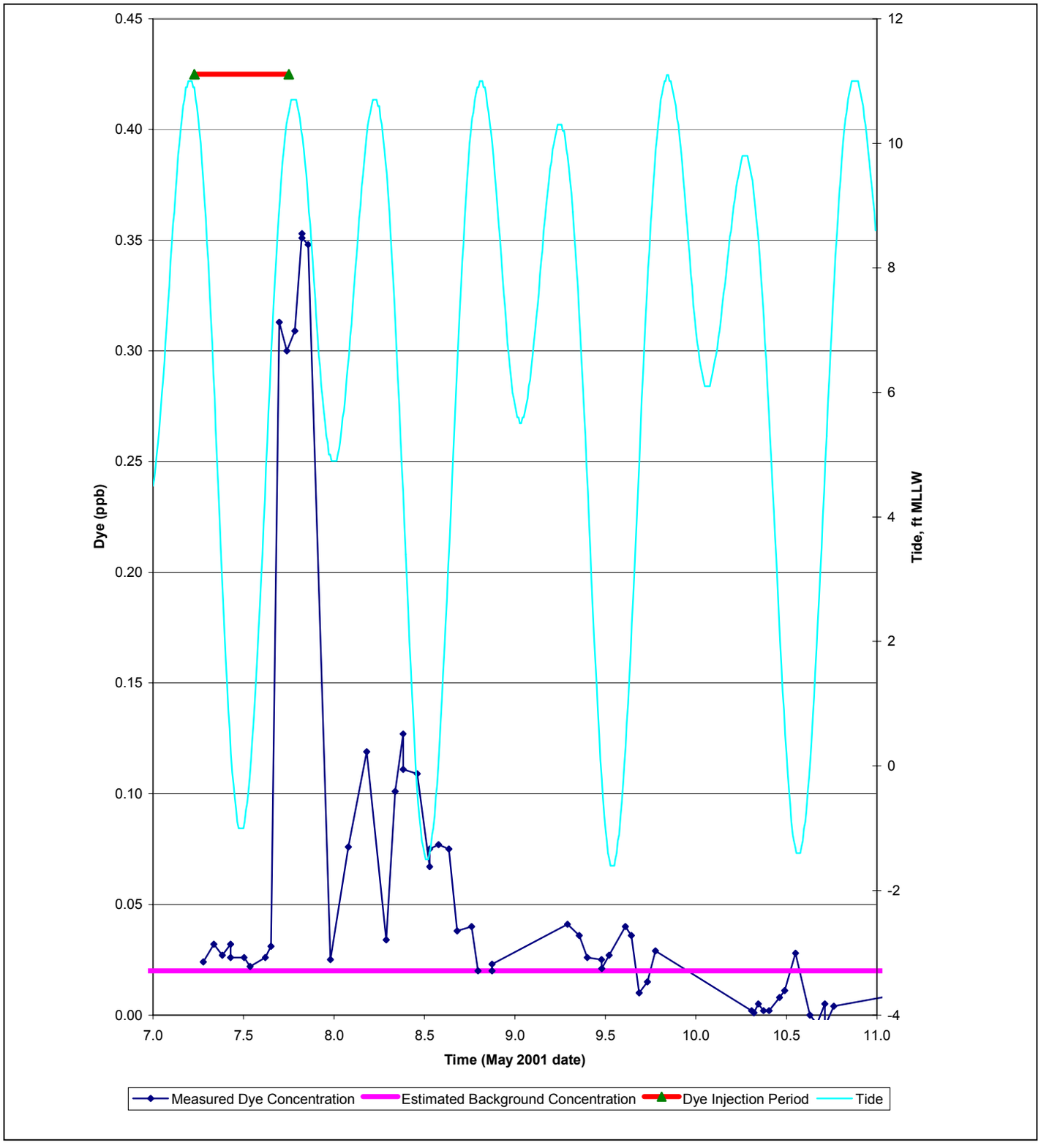


Figure G-7F. **Dye Study 3, South Browns Bay Station**

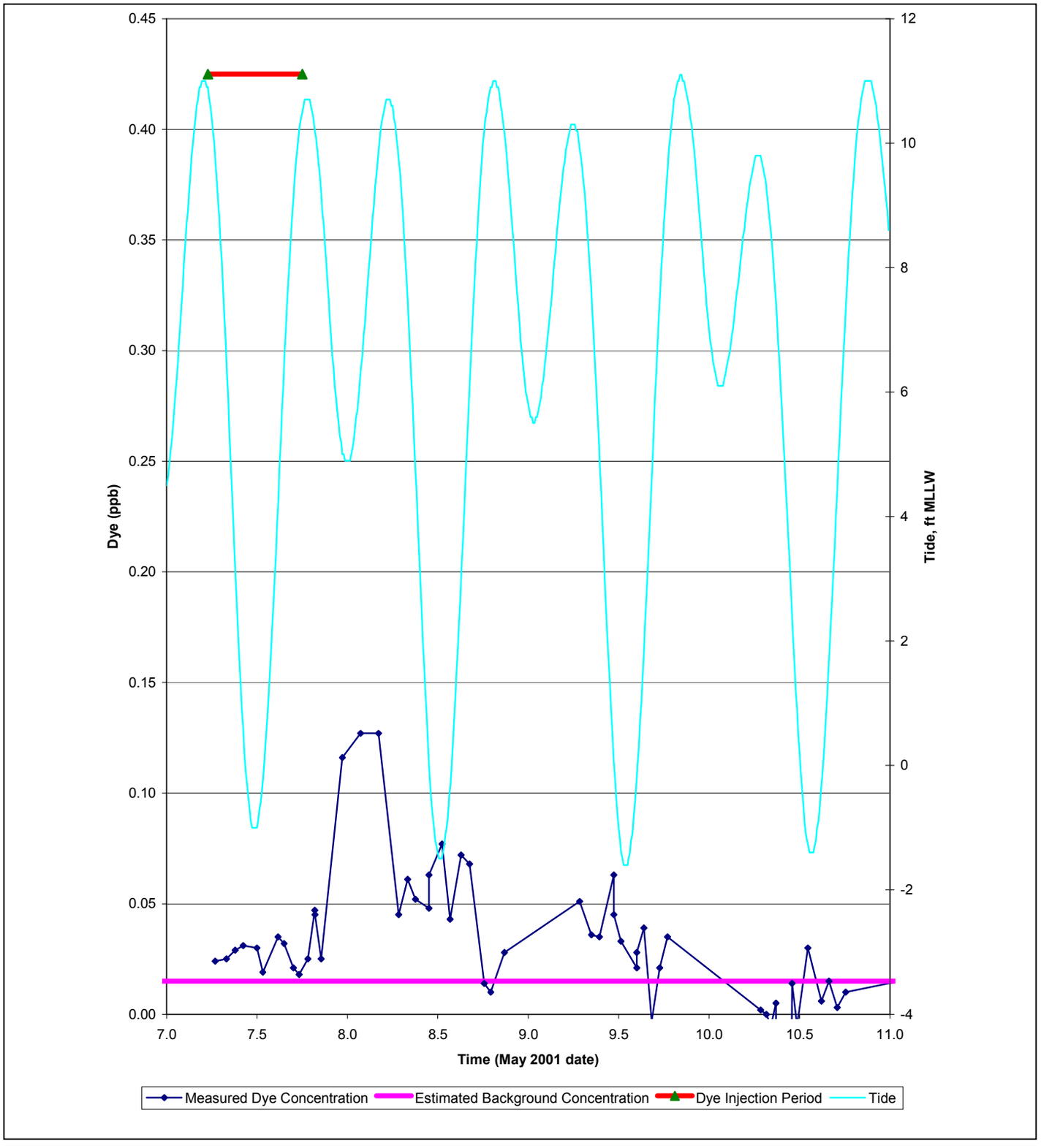


Figure G-7G. **Dye Study 3, Edmonds Autosampler**

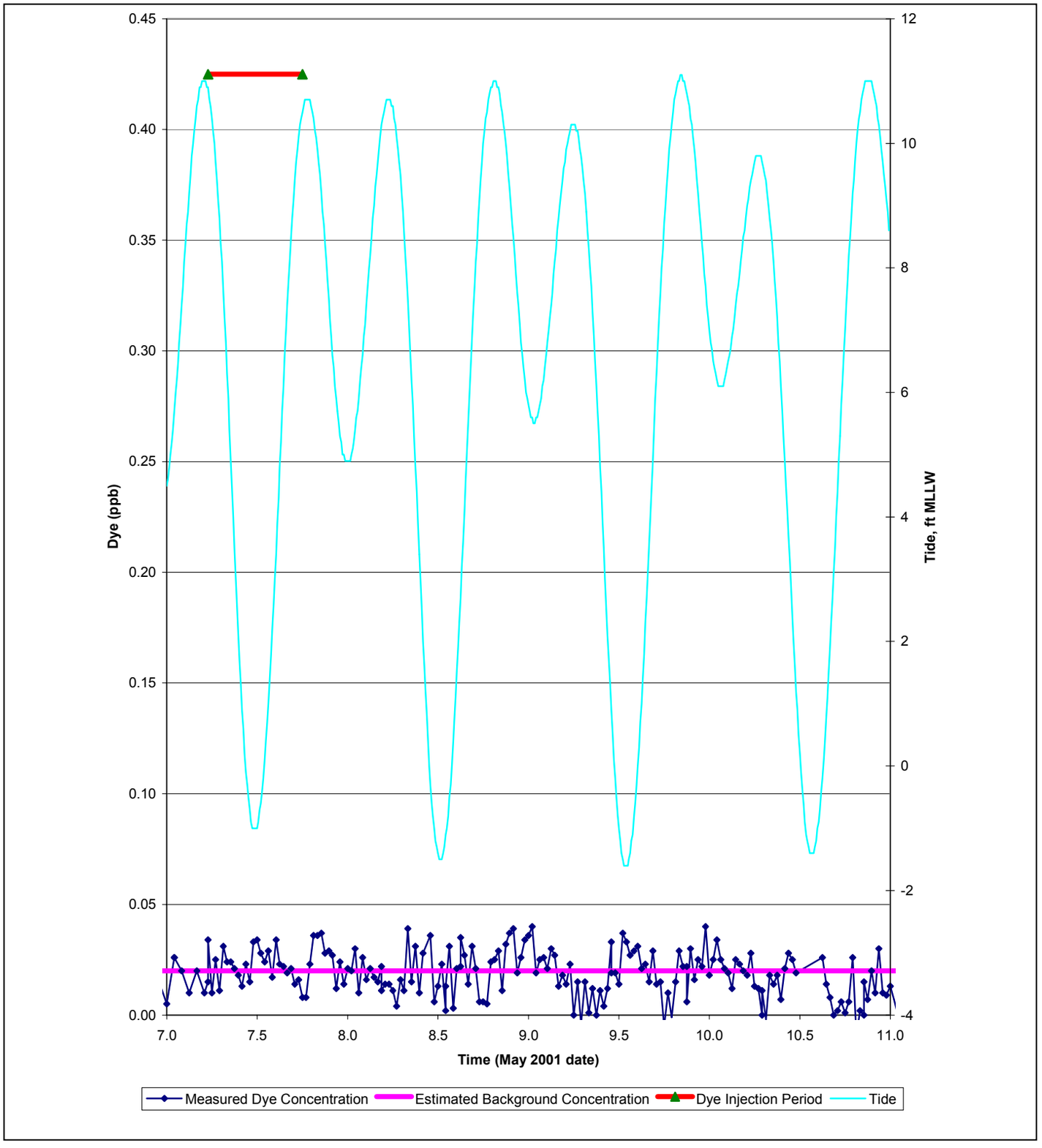
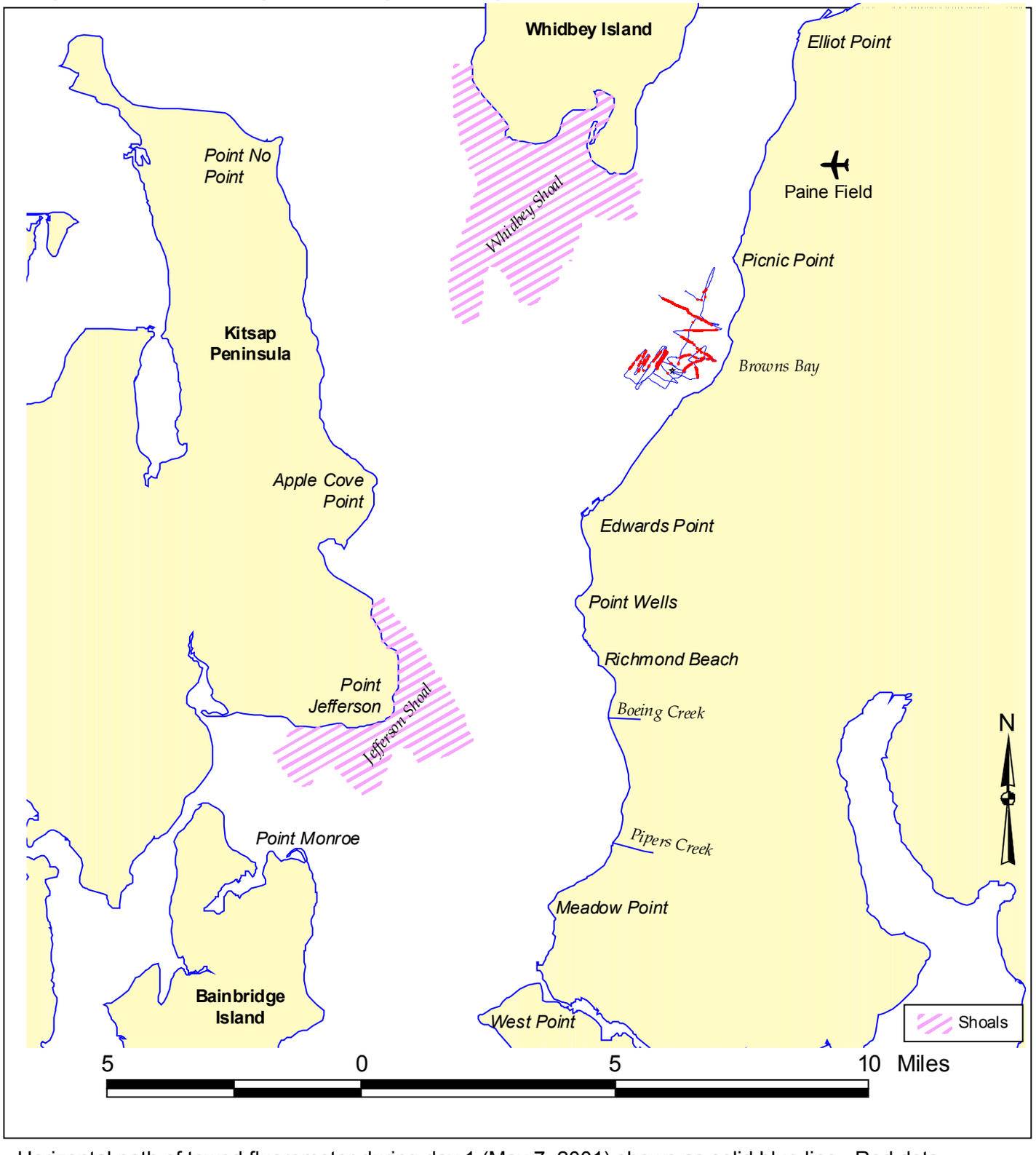
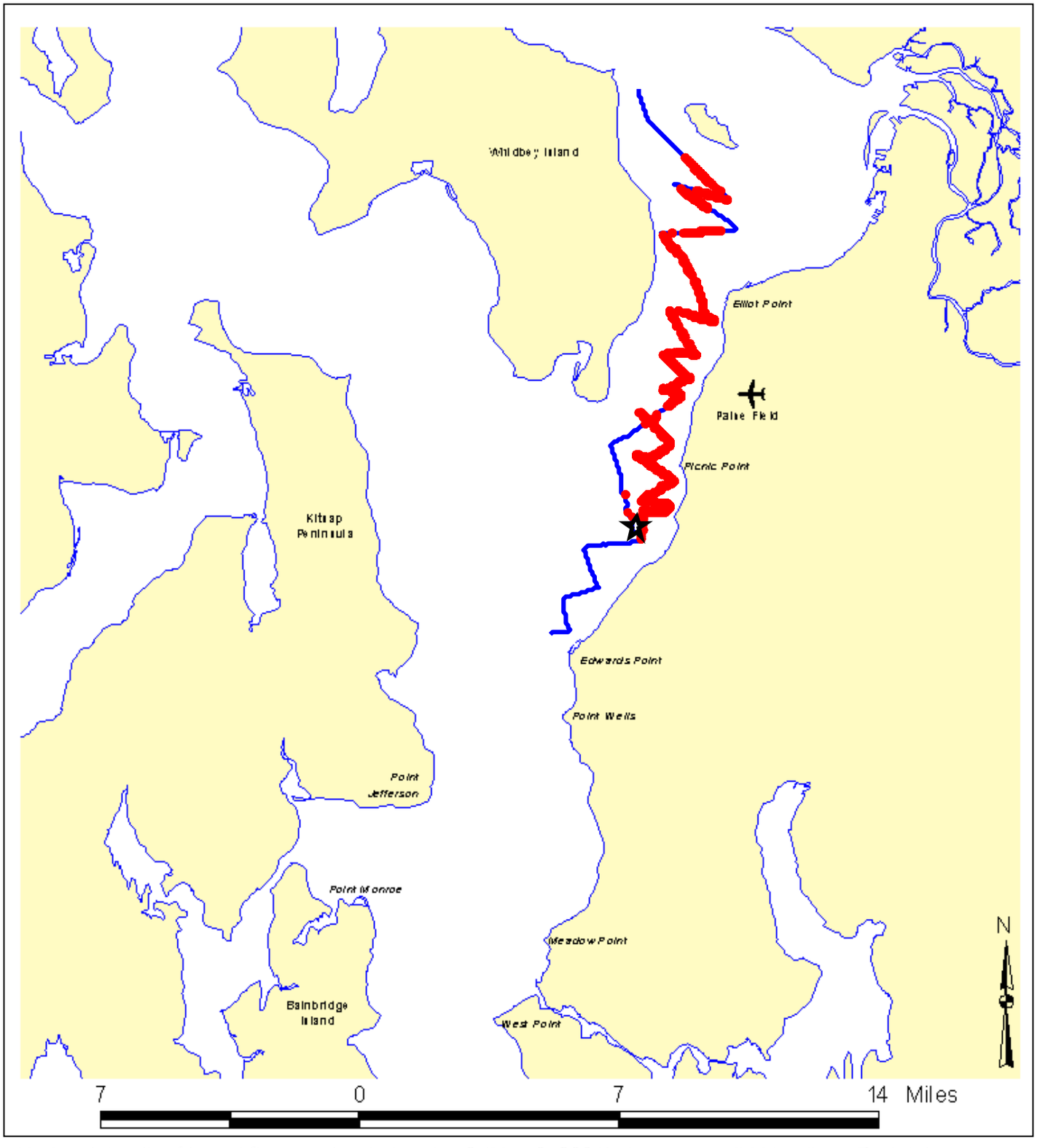


Figure G-7H. **Dye Study 3, Day 1 Towed Fluorometer Track**



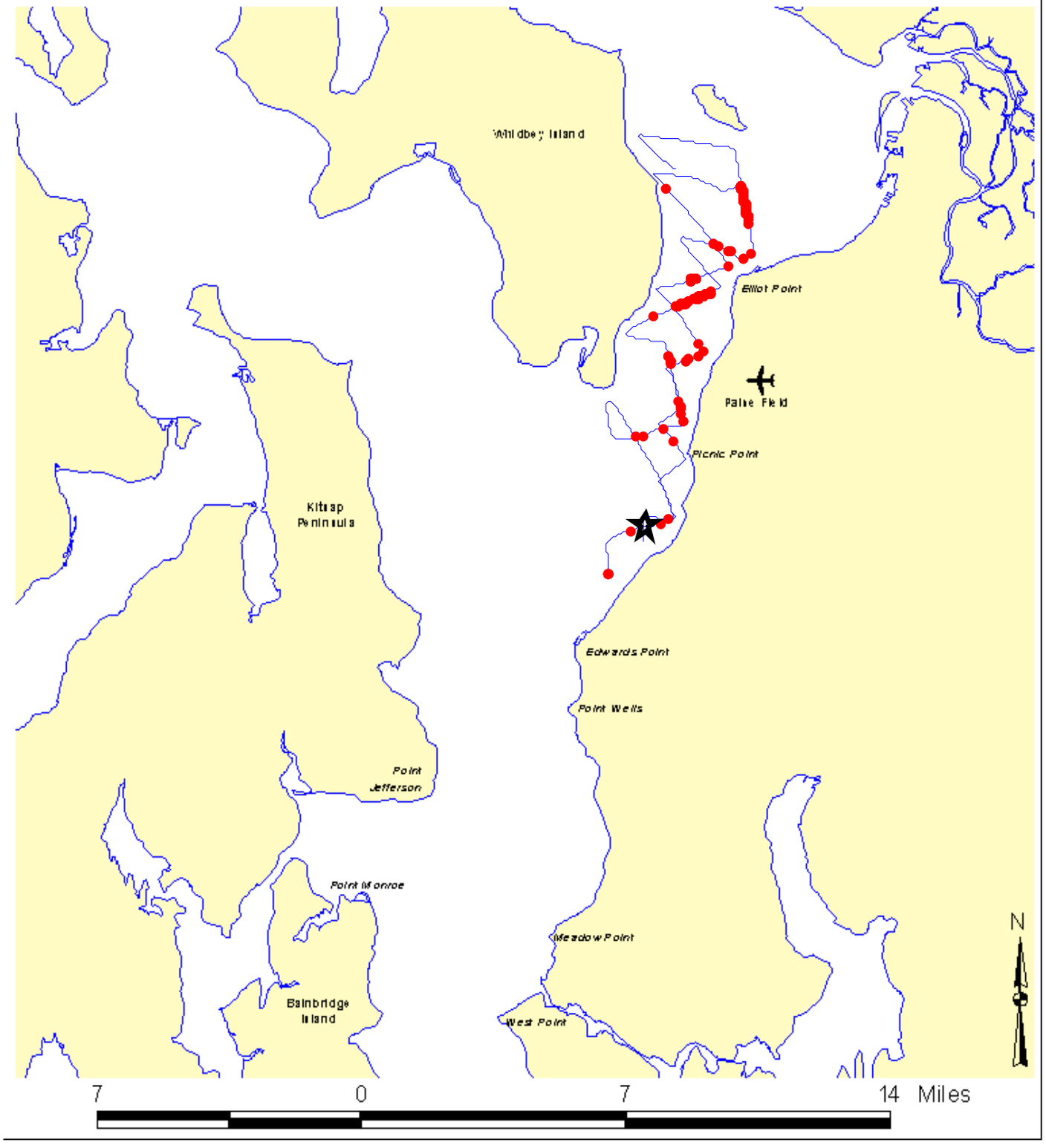
Horizontal path of towed fluorometer during day 1 (May 7, 2001) shown as solid blue line. Red dots represent locations with measured fluorescence levels indicating dye concentrations greater than 1 ppb. Black star indicates the dye release location.

Figure G-7l. **Dye Study 3, Day 2 Towed Fluorometer Track**



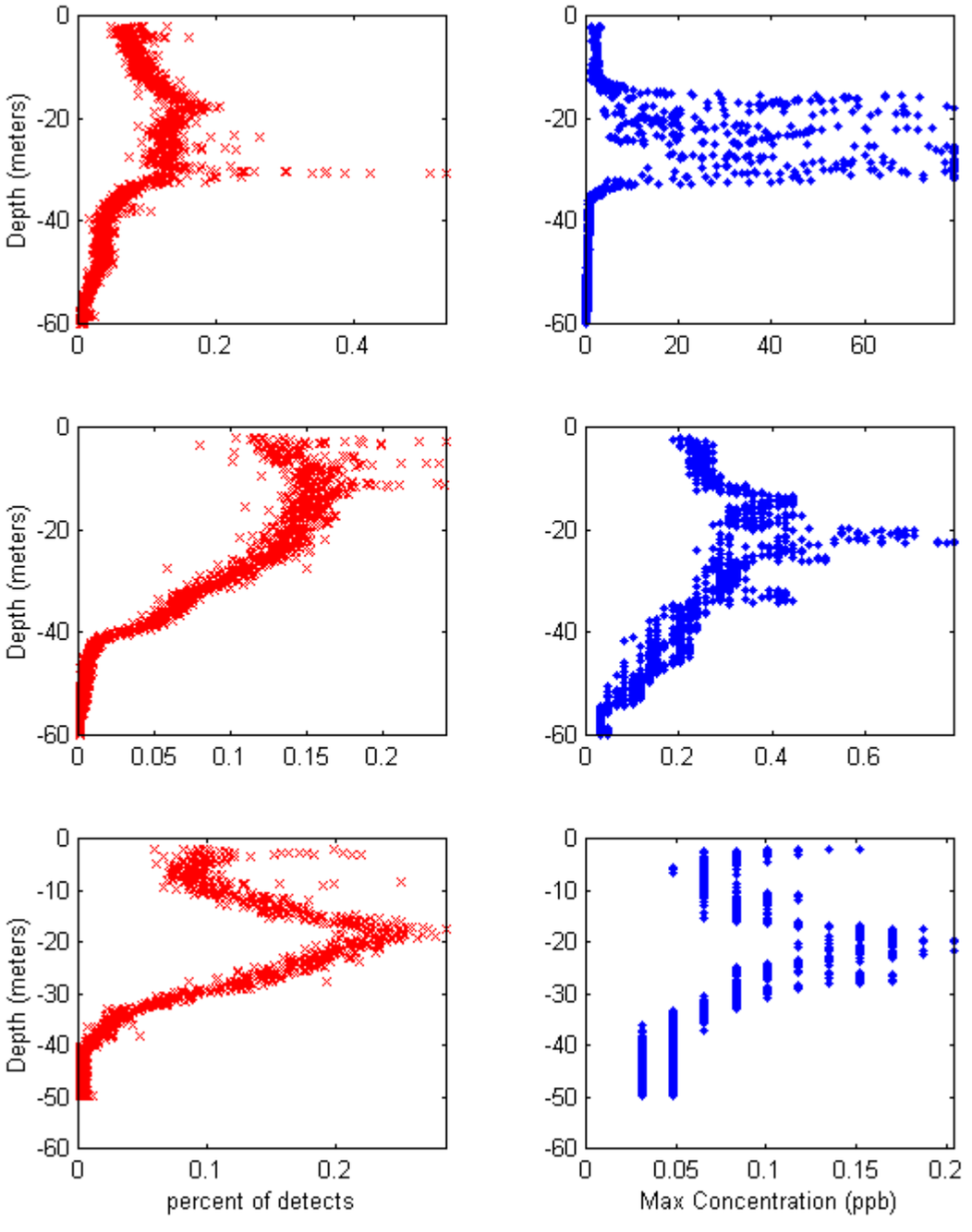
Horizontal path of towed fluorometer during day 2 (May 8, 2001) shown as solid blue line. Red dots represent locations with measured fluorescence levels indicating dye concentrations greater than 0.1 ppb. Black star indicates the dye release location.

Figure G-7J. Dye Study 3, Day 3 Towed Fluorometer Track



Horizontal path of towed fluorometer during day 3 (May 9, 2001) shown as solid blue line. Red dots represent locations with measured fluorescence levels indicating dye concentrations greater than 0.1 ppb. Black star indicates the dye release location.

Figure G-7H. **Dye Study 3, Depth Profile of Dye Observations**



Vertical distribution of dye observations. Left panel shows, of the samples above the detection limit, the percentage that occurred at each depth (total of all depths is 100%). Right panel shows the maximum concentration observed at each depth. Top panels are observations from day 1 (May 7, 2001), middle panels from day 2 (May 8, 2001), and bottom panels from day 3 (May 9, 2001).

Figure G-8A. **Dye Study 4, Meadowdale Marina Autosampler**

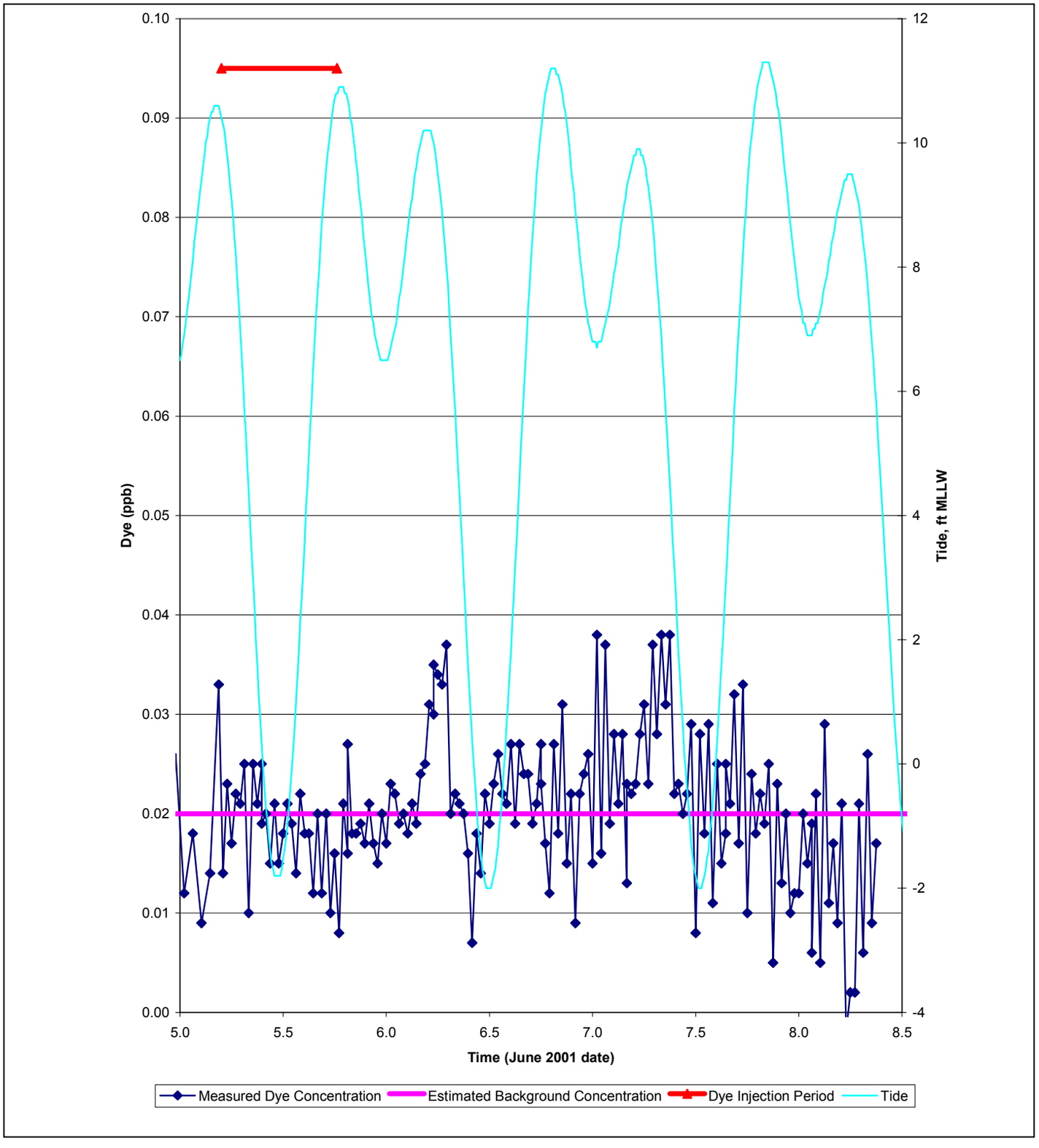


Figure G-8B. **Dye Study 4, Browns Bay Station**

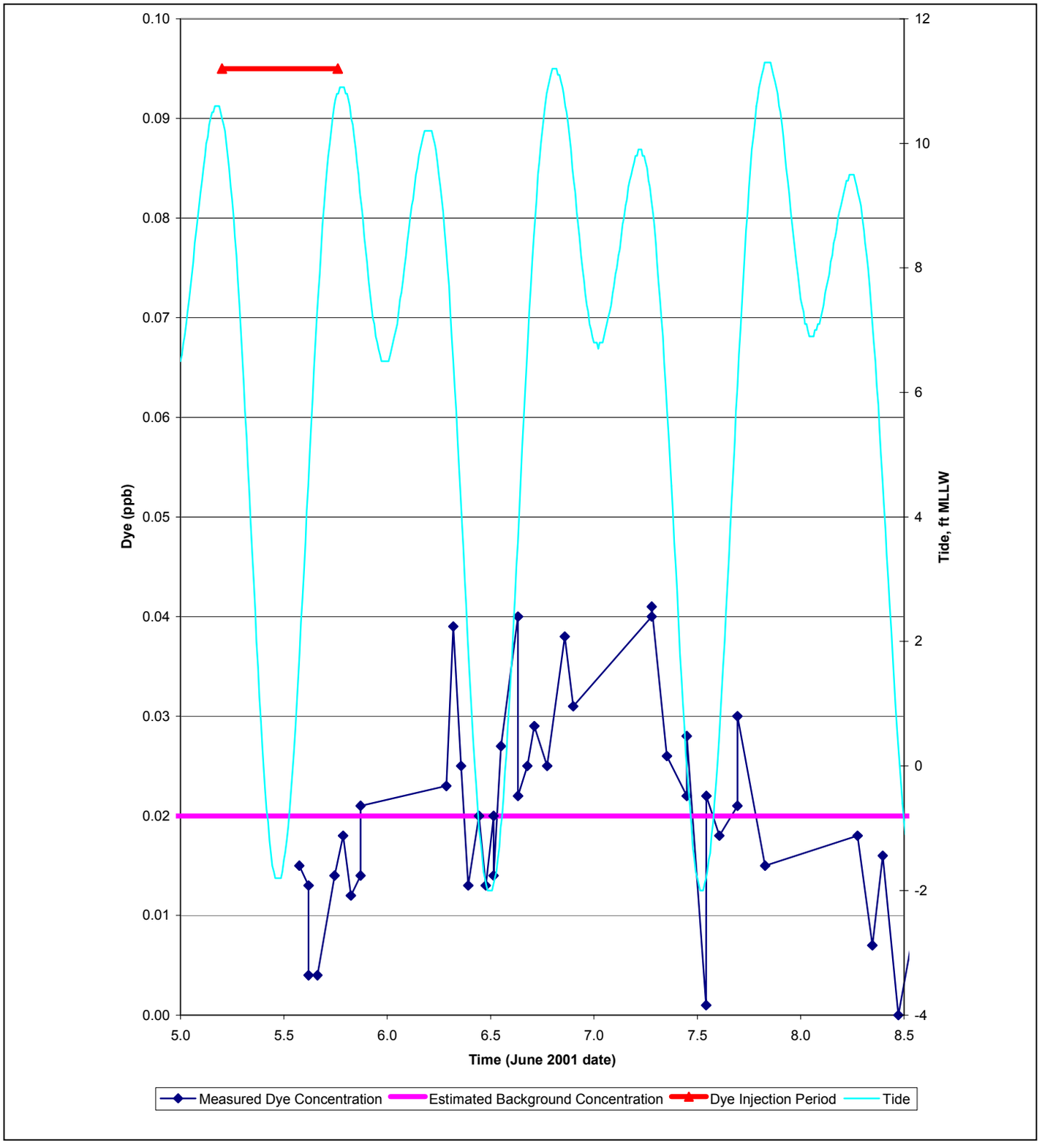


Figure G-8C. **Dye Study 4, Edmonds Autosampler**

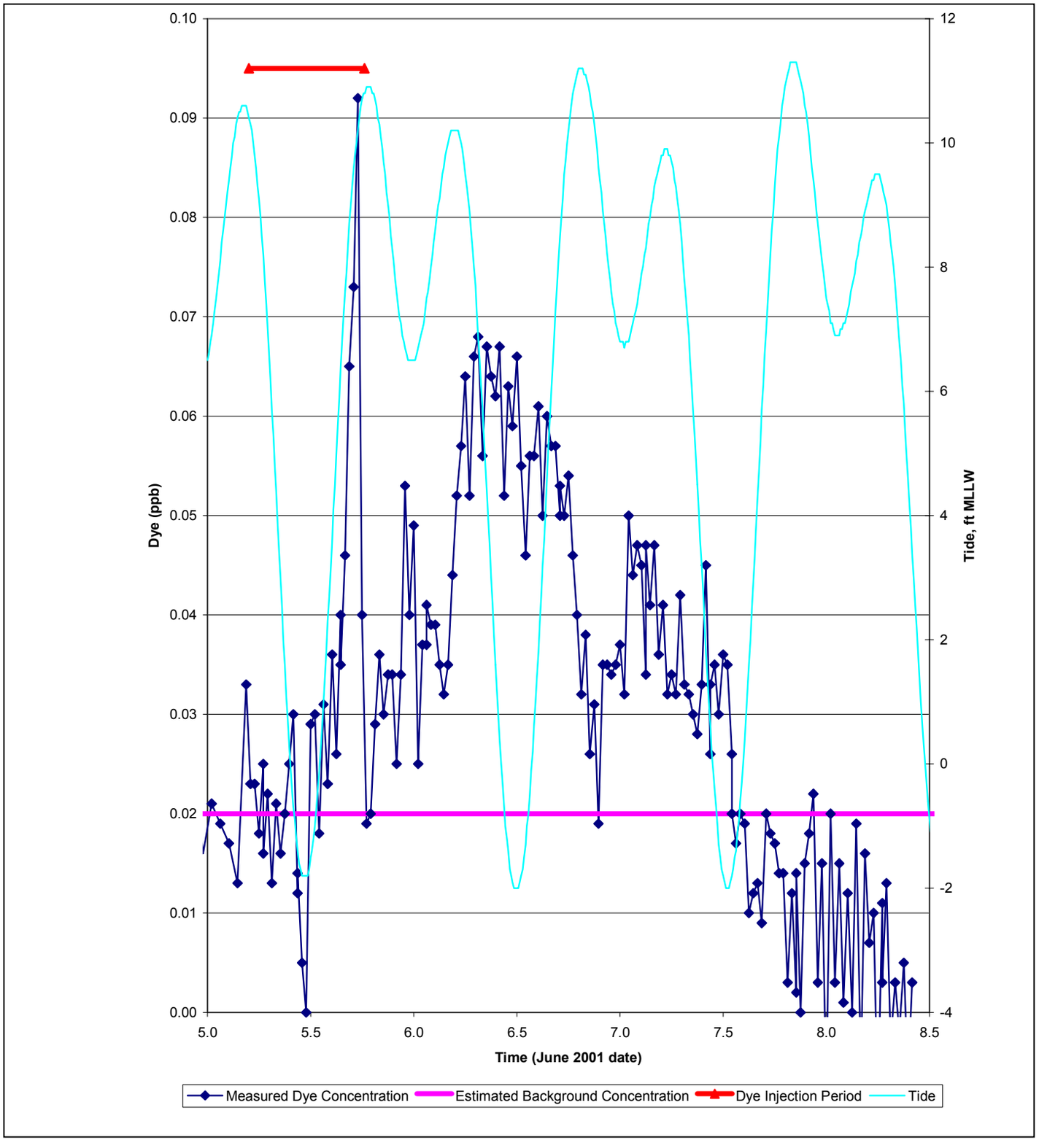


Figure G-8D. **Dye Study 4, Edwards Point Autosampler**

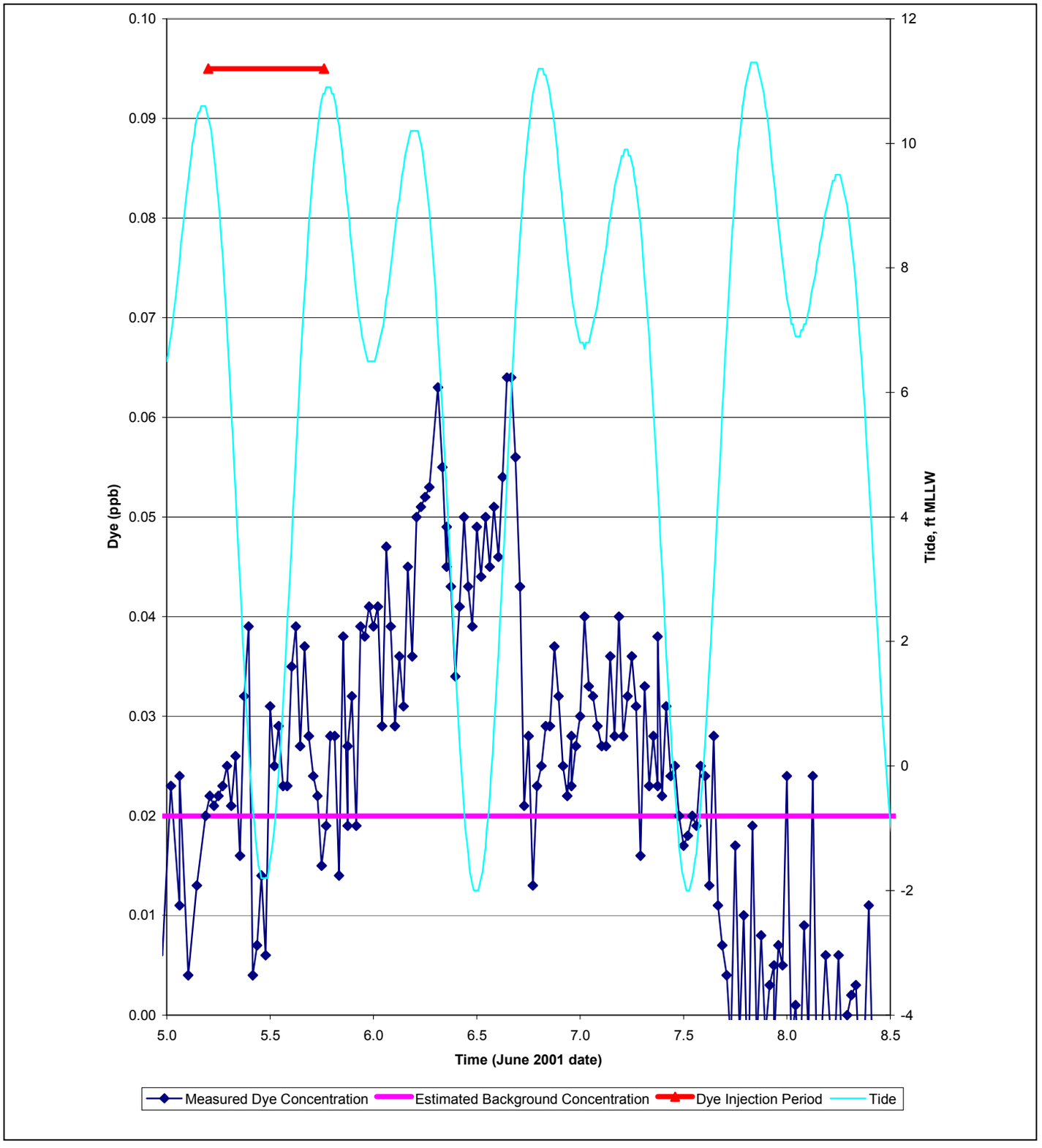


Figure G-8E. **Dye Study 4, Deer Creek Station**

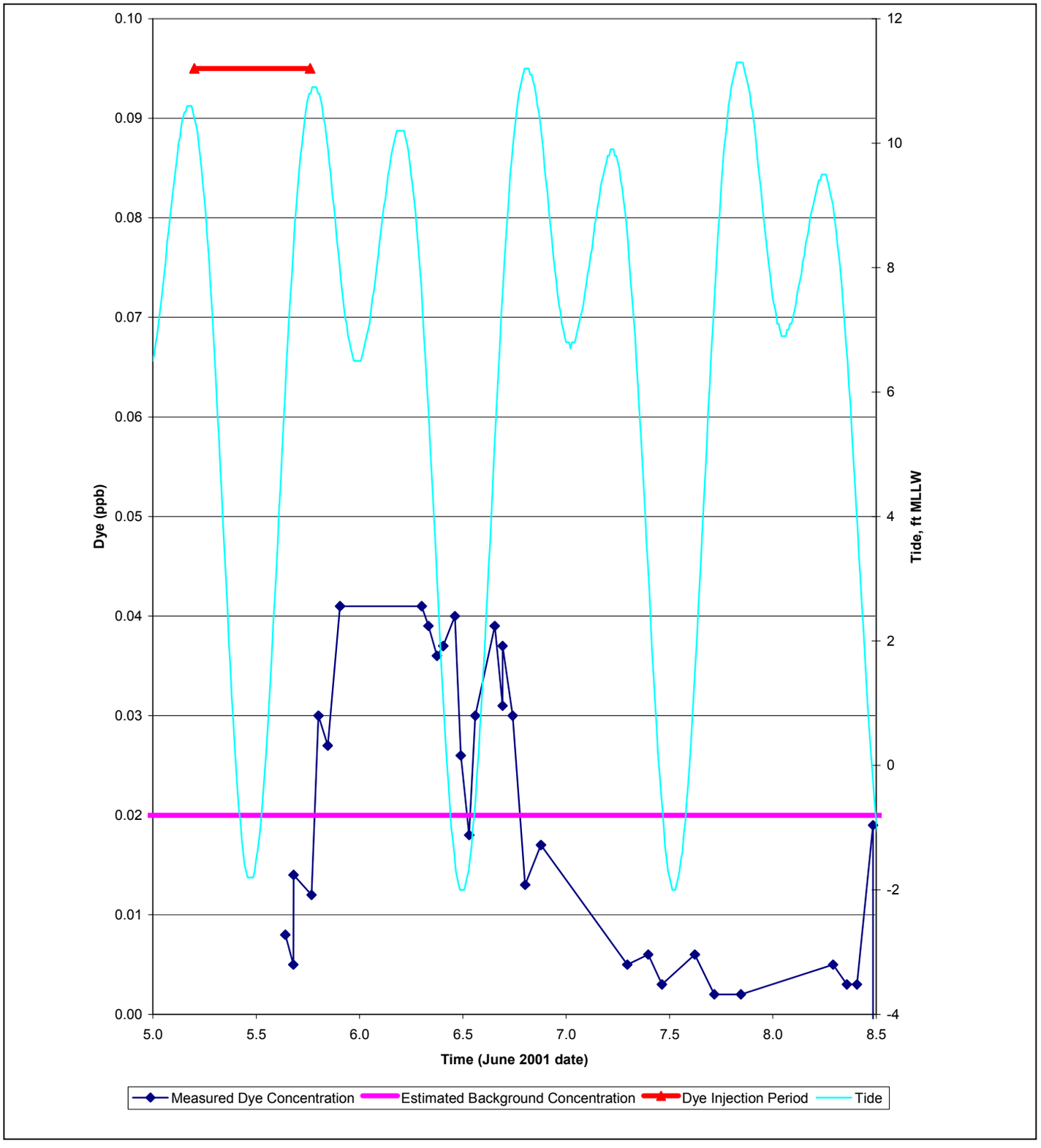


Figure G-8F. **Dye Study 4, Richmond Beach Pump Station**

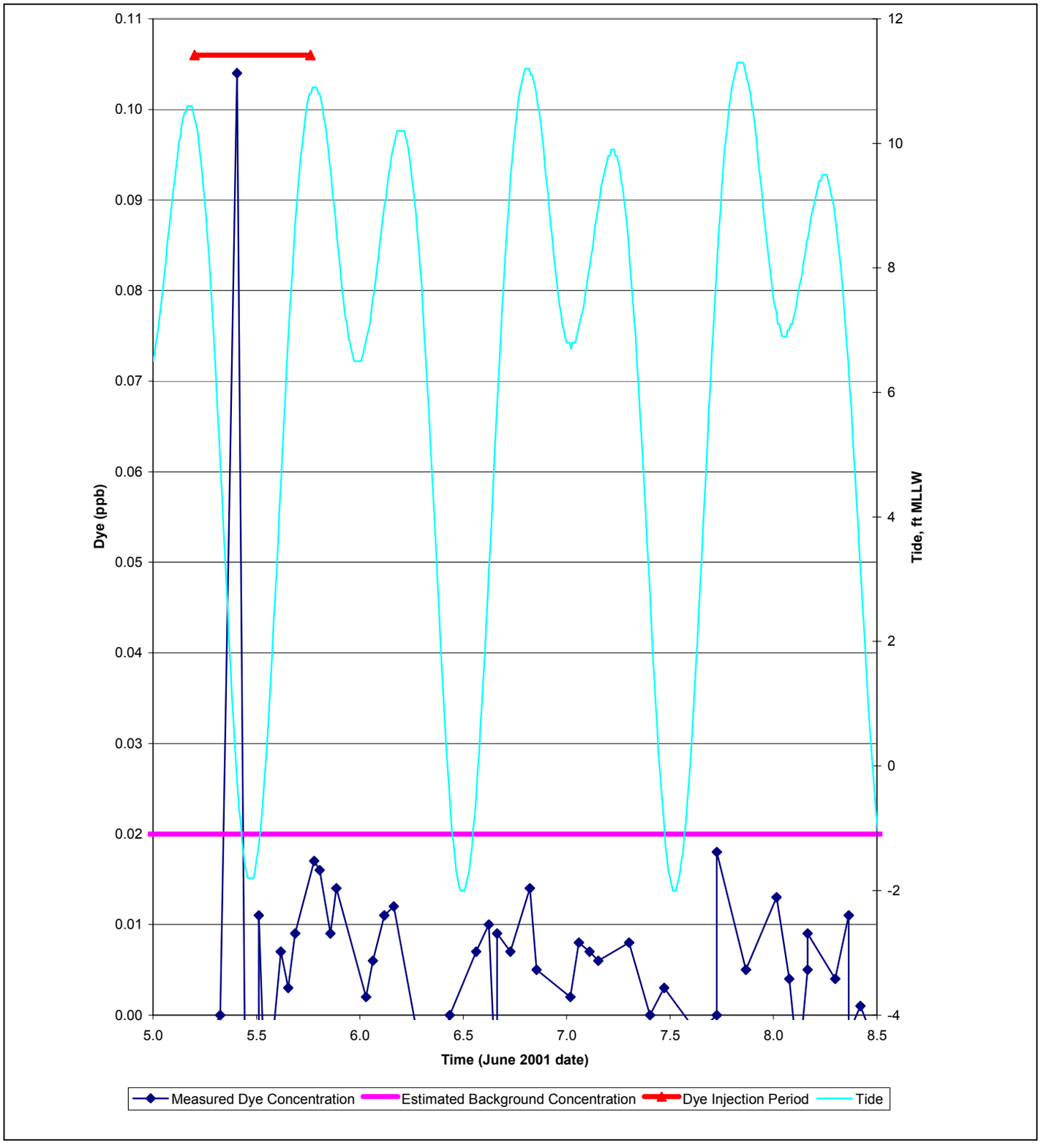


Figure G-8G. **Dye Study 4, North Richmond Beach Station**

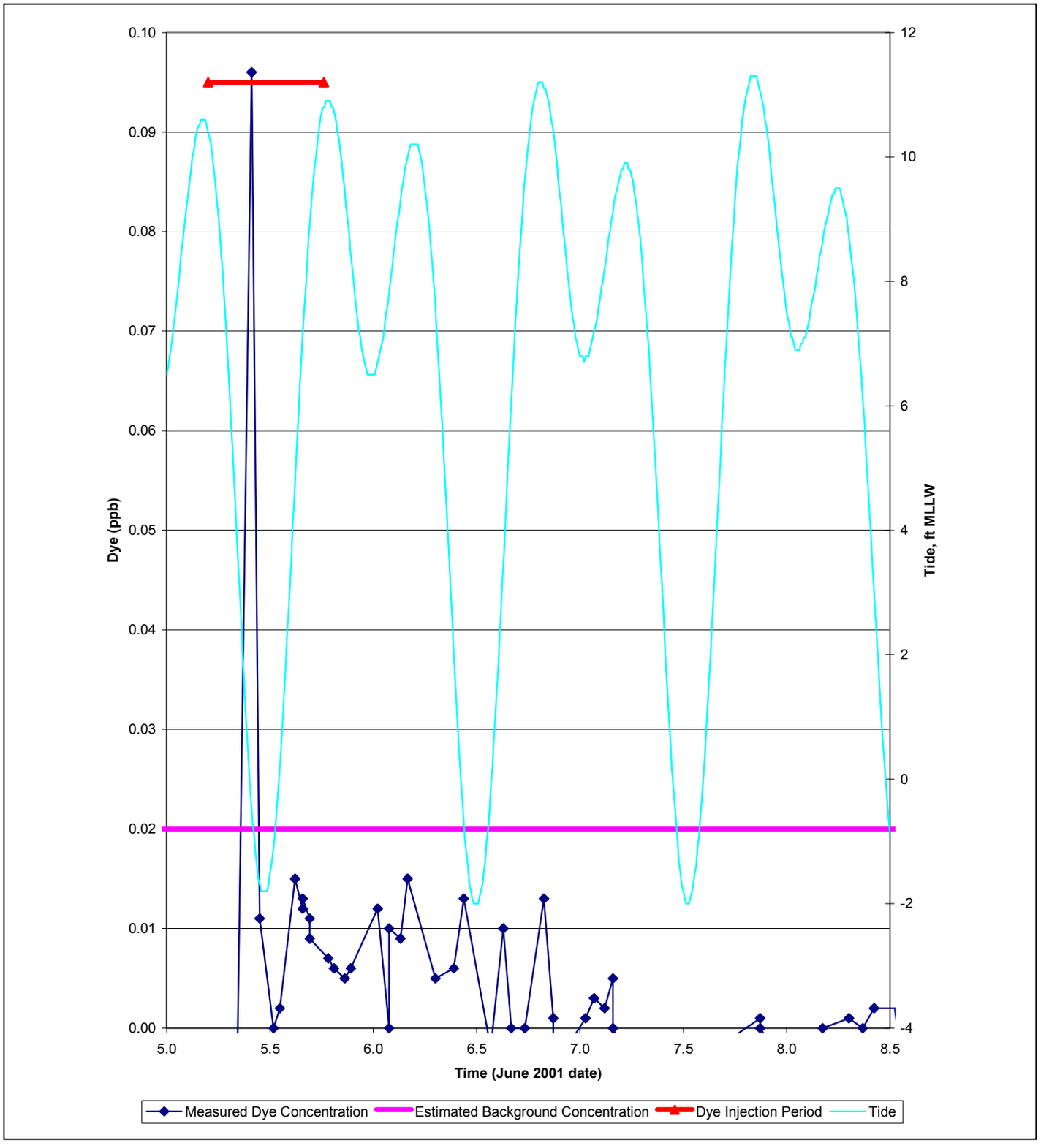
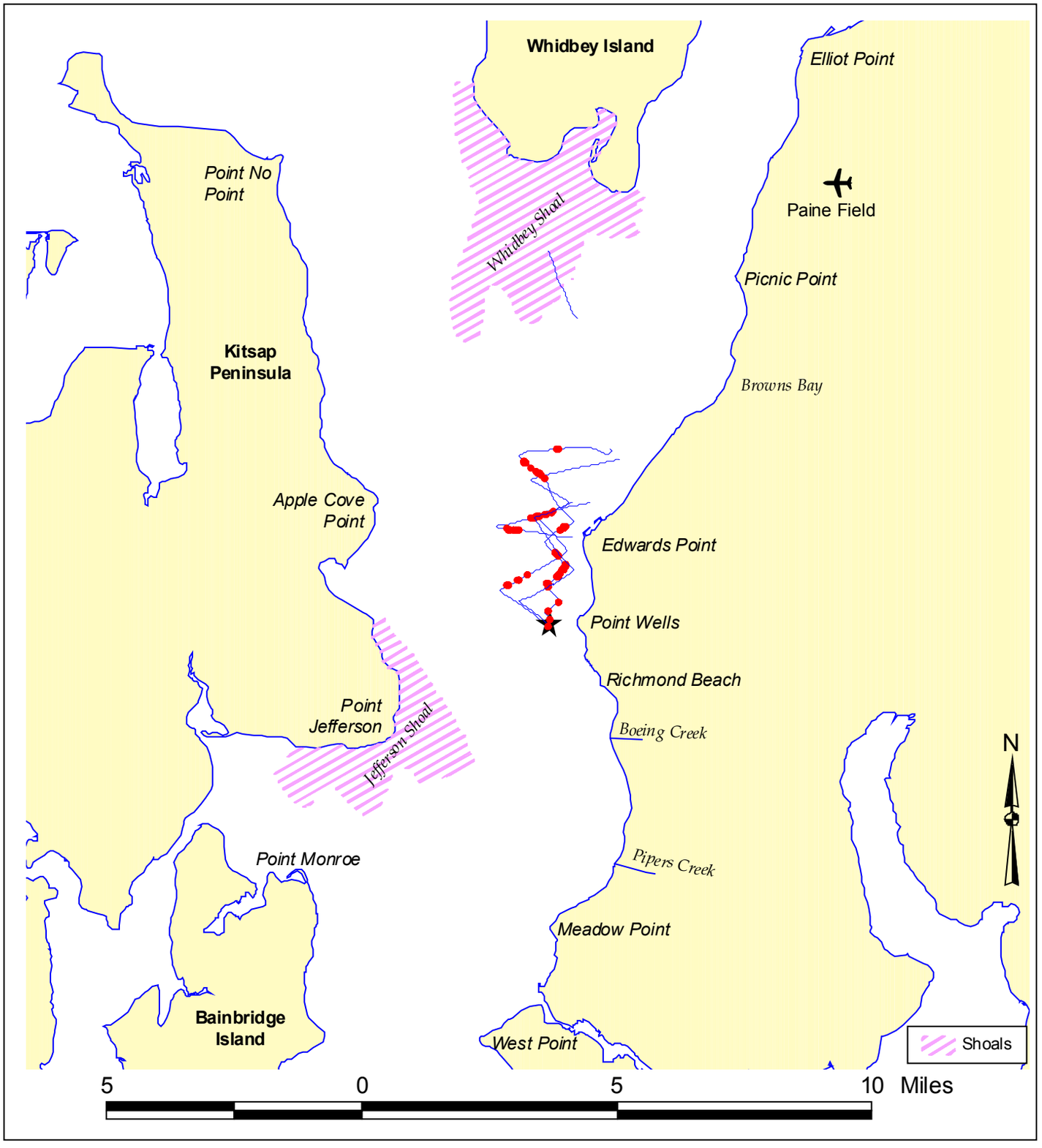
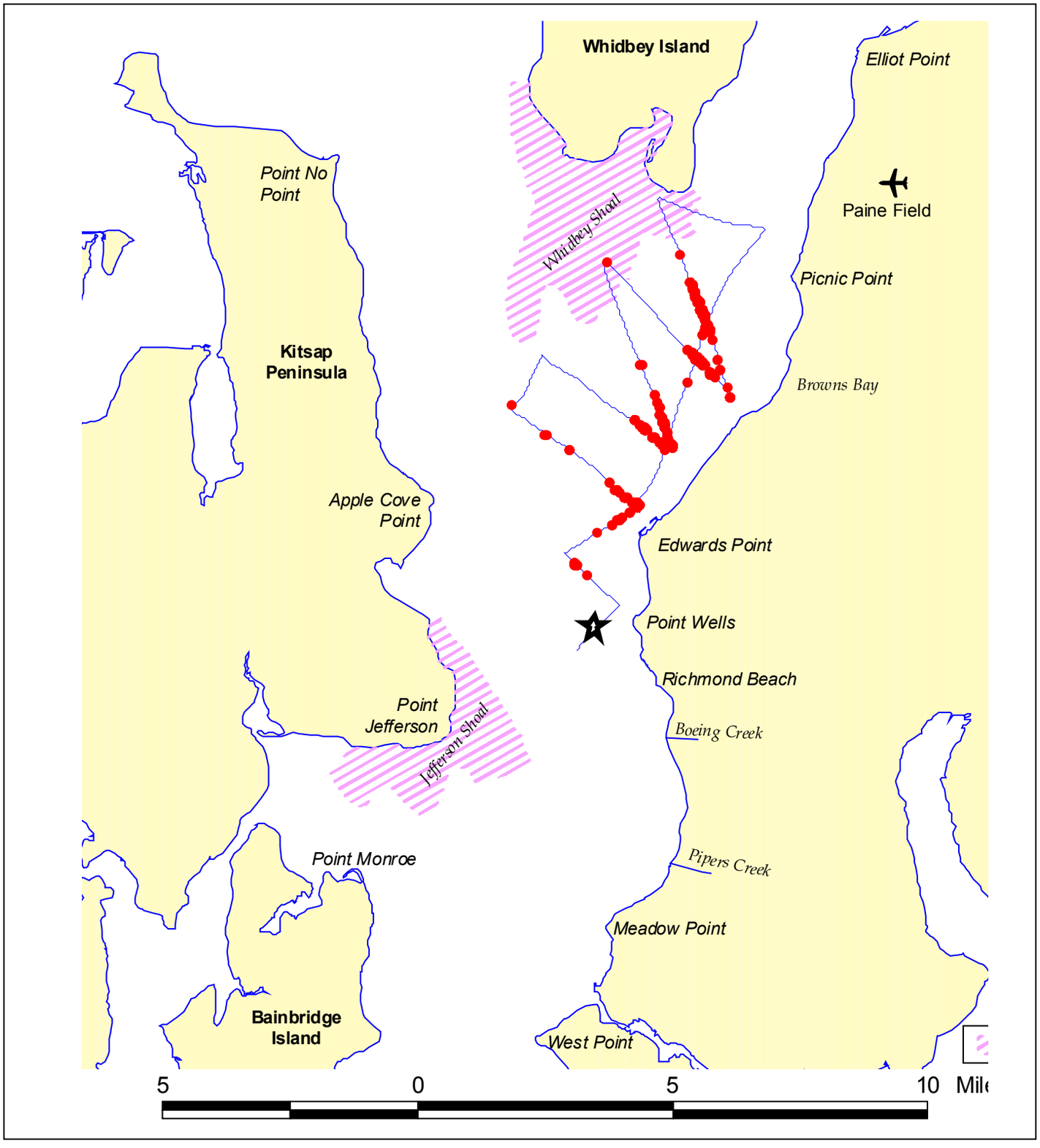


Figure G-8H. **Dye Study 4, Day 1 Towed Fluorometer Track**



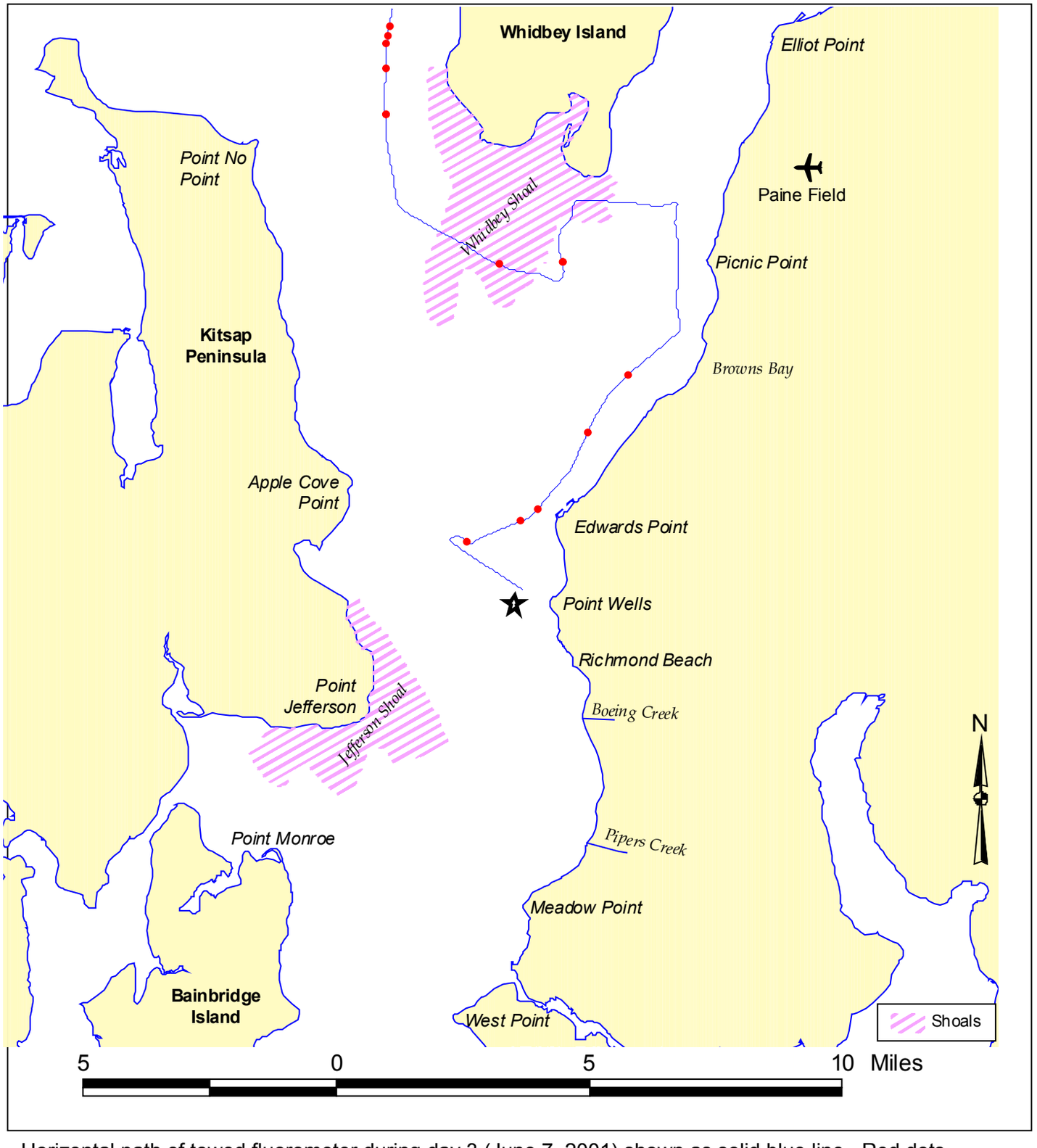
Horizontal path of towed fluorometer during day 1 (June 5, 2001) shown as solid blue line. Red dots represent locations with measured fluorescence levels indicating dye concentrations greater than 1 ppb. Black star indicates the dye release location.

Figure G-8l. **Dye Study 4, Day 2 Towed Fluorometer Track**



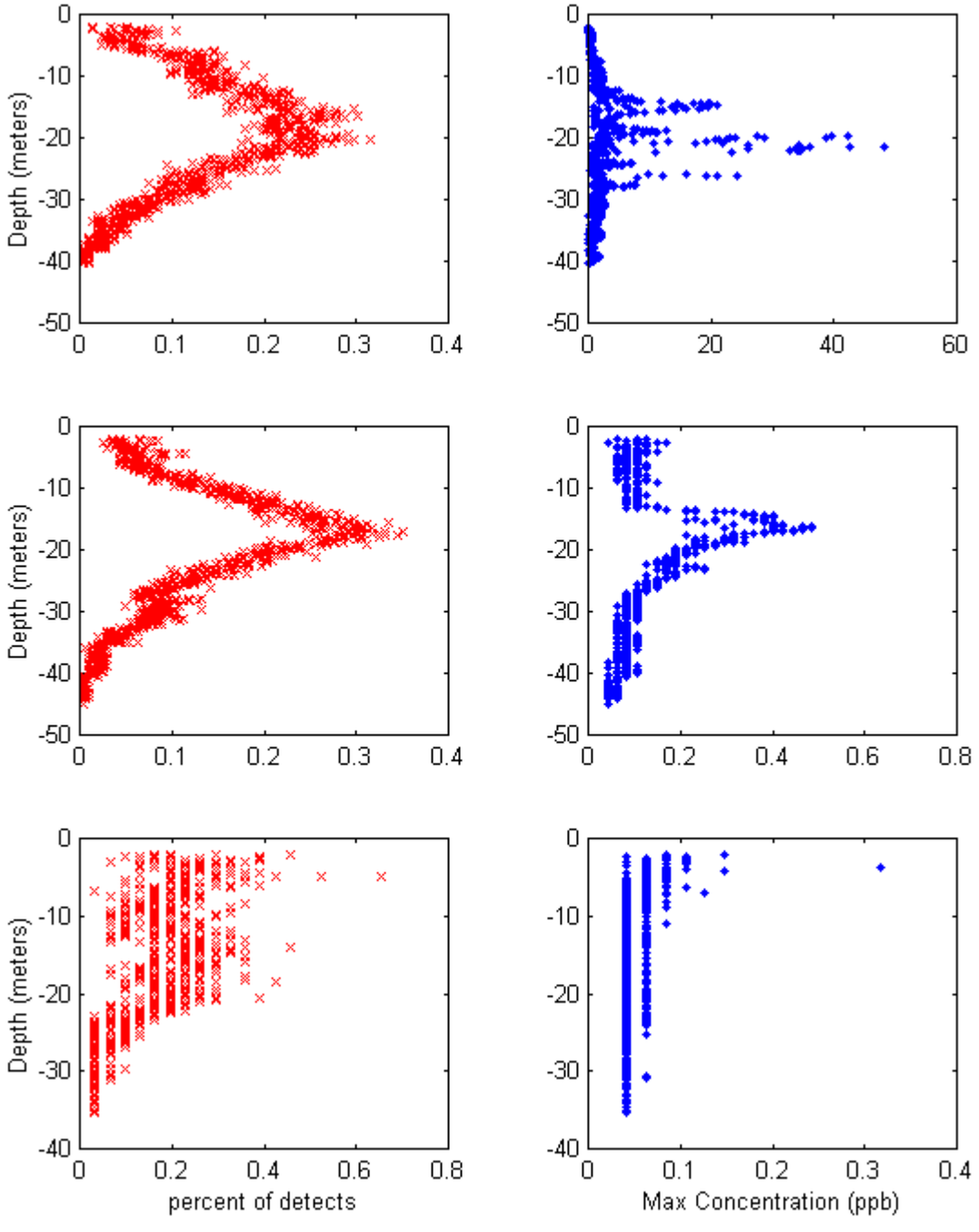
Horizontal path of towed fluorometer during day 2 (June 6, 2001) shown as solid blue line. Red dots represent locations with measured fluorescence levels indicating dye concentrations greater than 0.1 ppb. Black star indicates the dye release location.

Figure G-8J. **Dye Study 4, Day 3 Towed Fluorometer Track**



Horizontal path of towed fluorometer during day 3 (June 7, 2001) shown as solid blue line. Red dots represent locations with measured fluorescence levels indicating dye concentrations greater than 0.1 ppb. Black star indicates the dye release location.

Figure G-8K. **Dye Study 4, Depth Profile of Dye Observations**



Vertical distribution of dye observations. Left panel shows, of the samples above the detection limit, the percentage that occurred at each depth (total of all depths is 100%). Right panel shows the maximum concentration observed at each depth. Top panels are observations from day 1 (June 5, 2001), middle panels from day 2 (June 6, 2001), and bottom panels from day 3 (June 7, 2001).

Figure G-9A. **Dye Study 5, Meadowdale Beach Station**

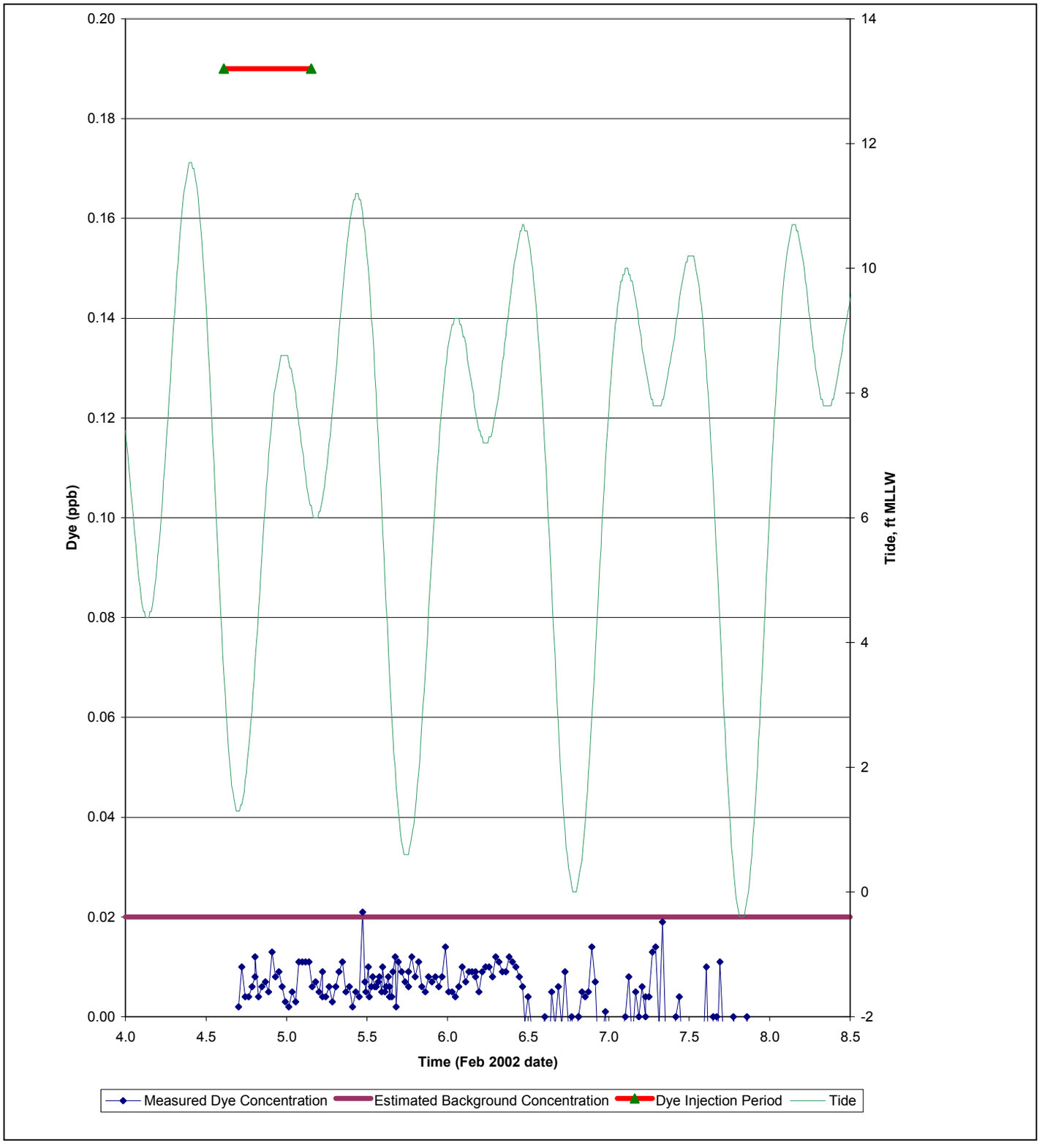


Figure G-9B. **Dye Study 5, Edmonds Autosampler**

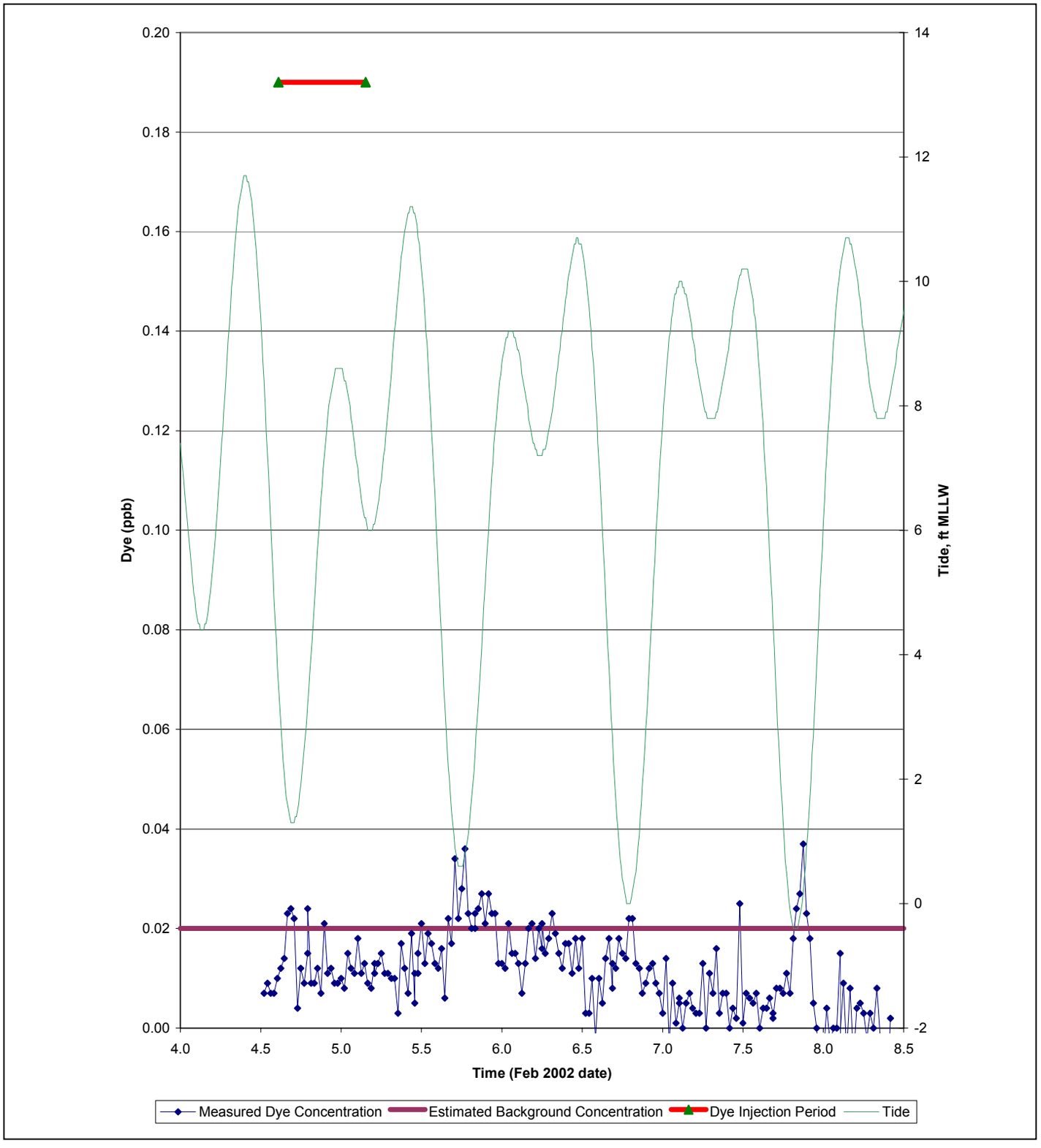


Figure G-9C. **Dye Study 5, Point Wells Autosampler**

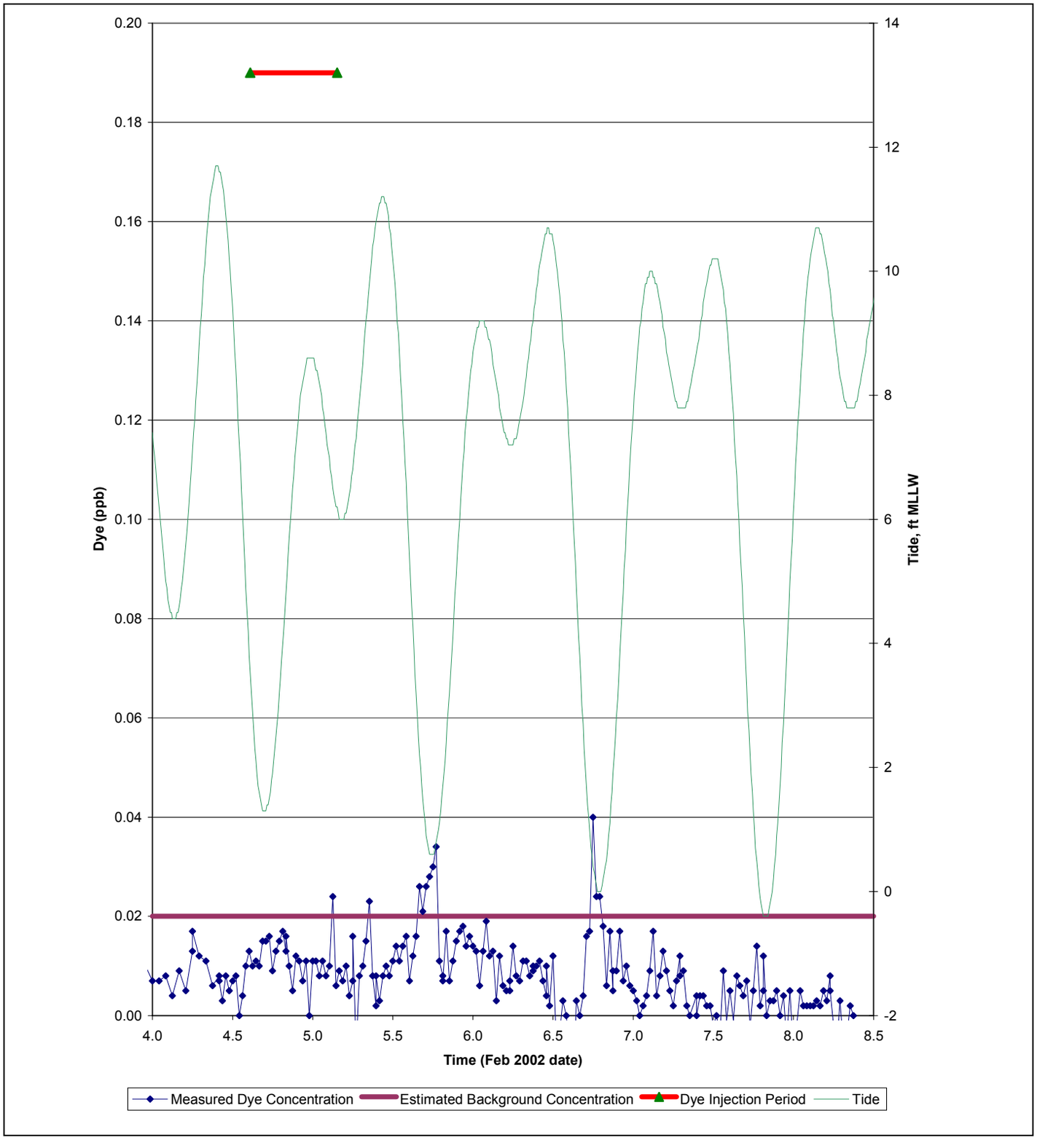


Figure G-9D. **Dye Study 5, Richmond Beach Station**

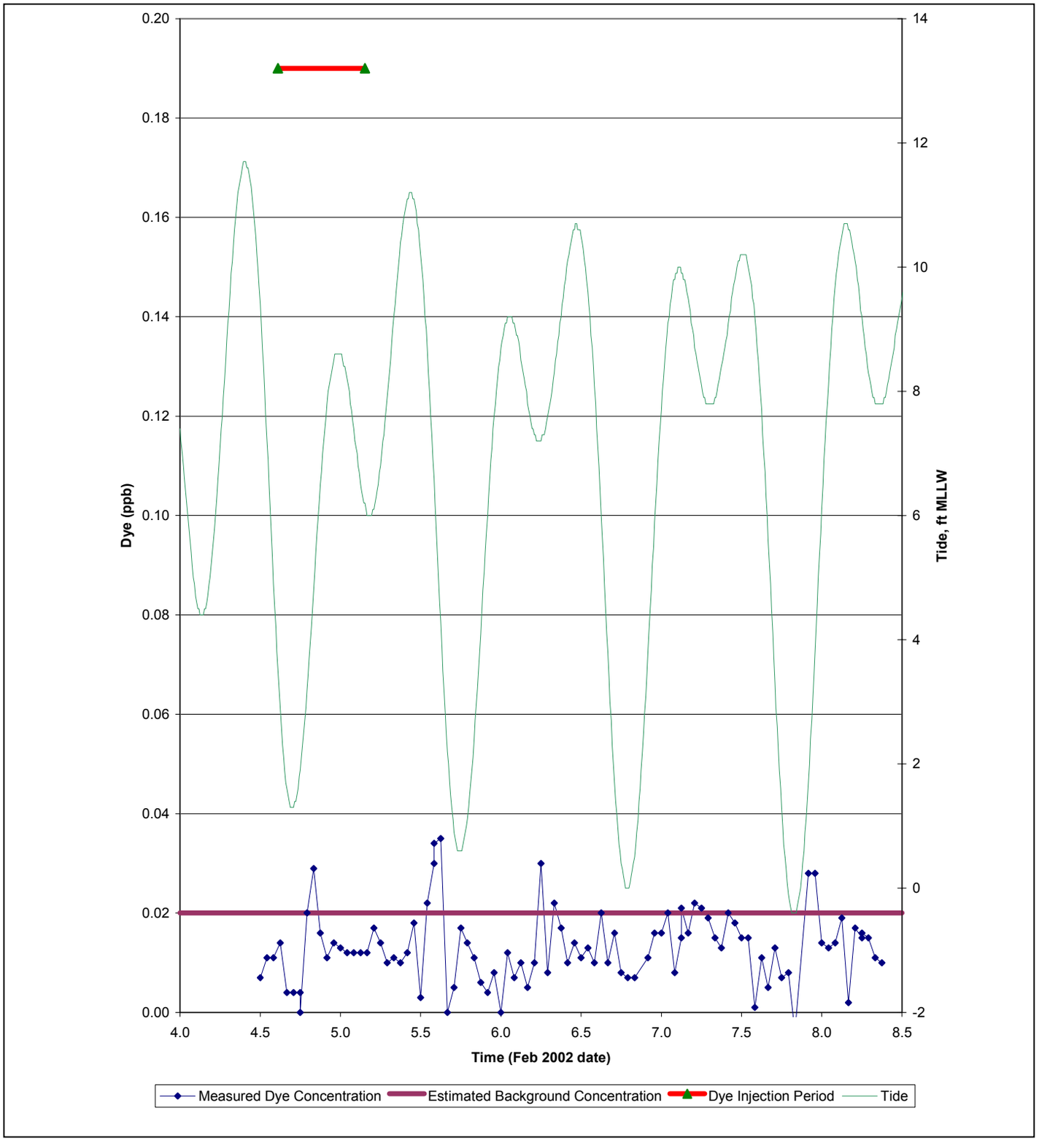
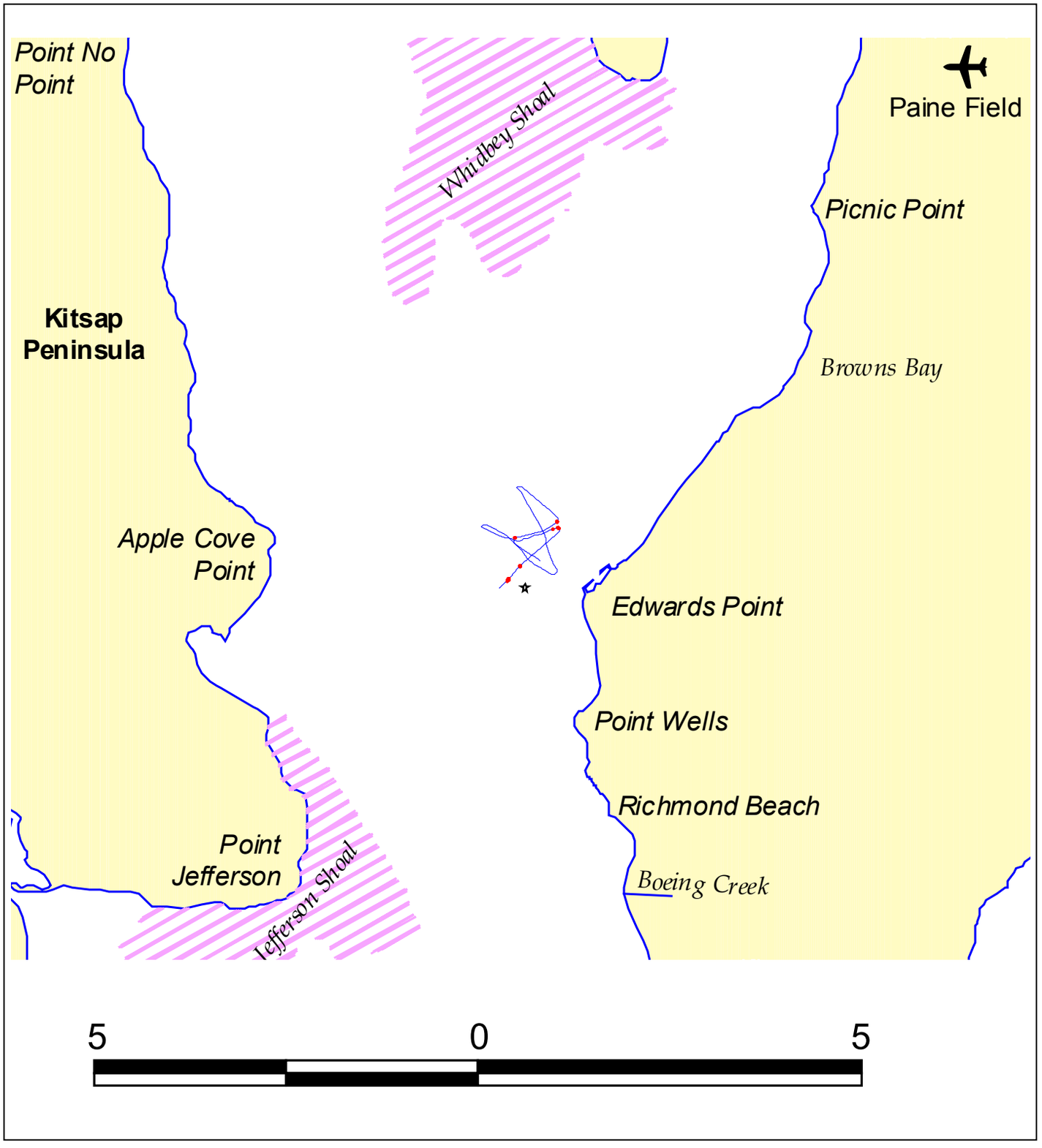
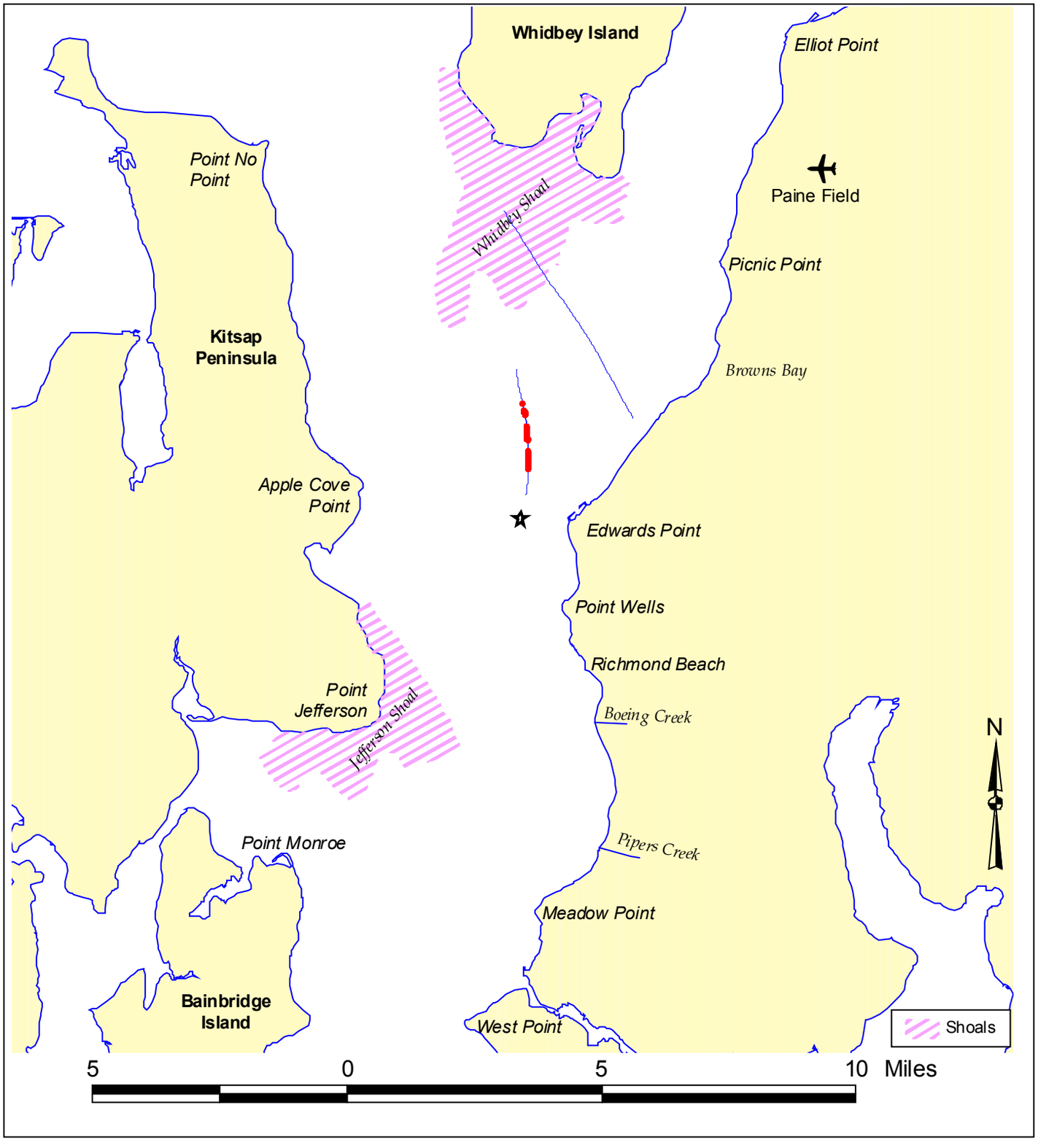


Figure G-9E. **Dye Study 5, Day 1 Towed Fluorometer Track**



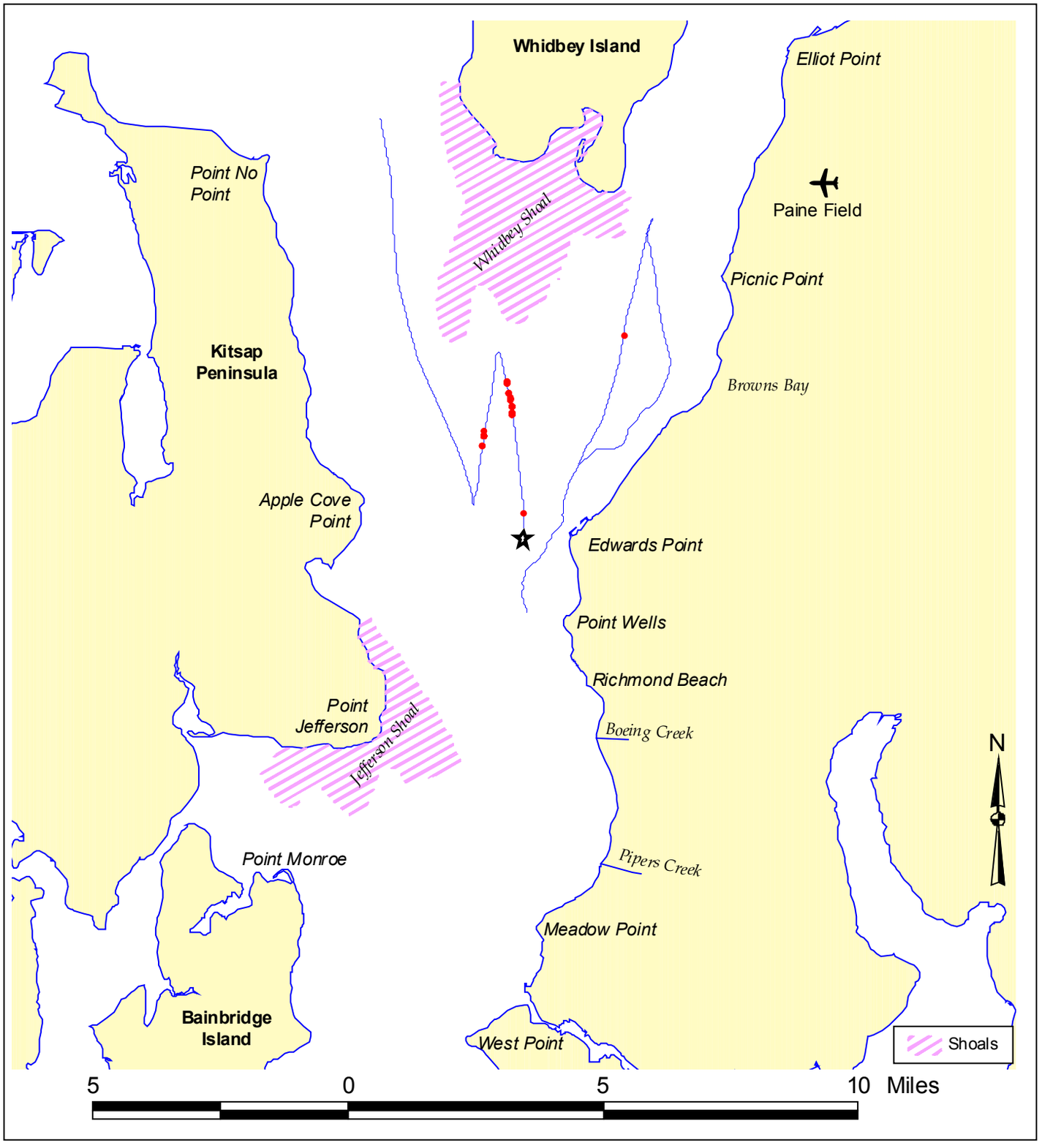
Horizontal path of towed fluorometer during day 1 (February 4, 2002) shown as solid blue line. Red dots represent locations with measured fluorescence levels indicating dye concentrations greater than 1 ppb. Black star indicates the dye release location.

Figure G-9F. **Dye Study 5, Day 2 Towed Fluorometer Track**



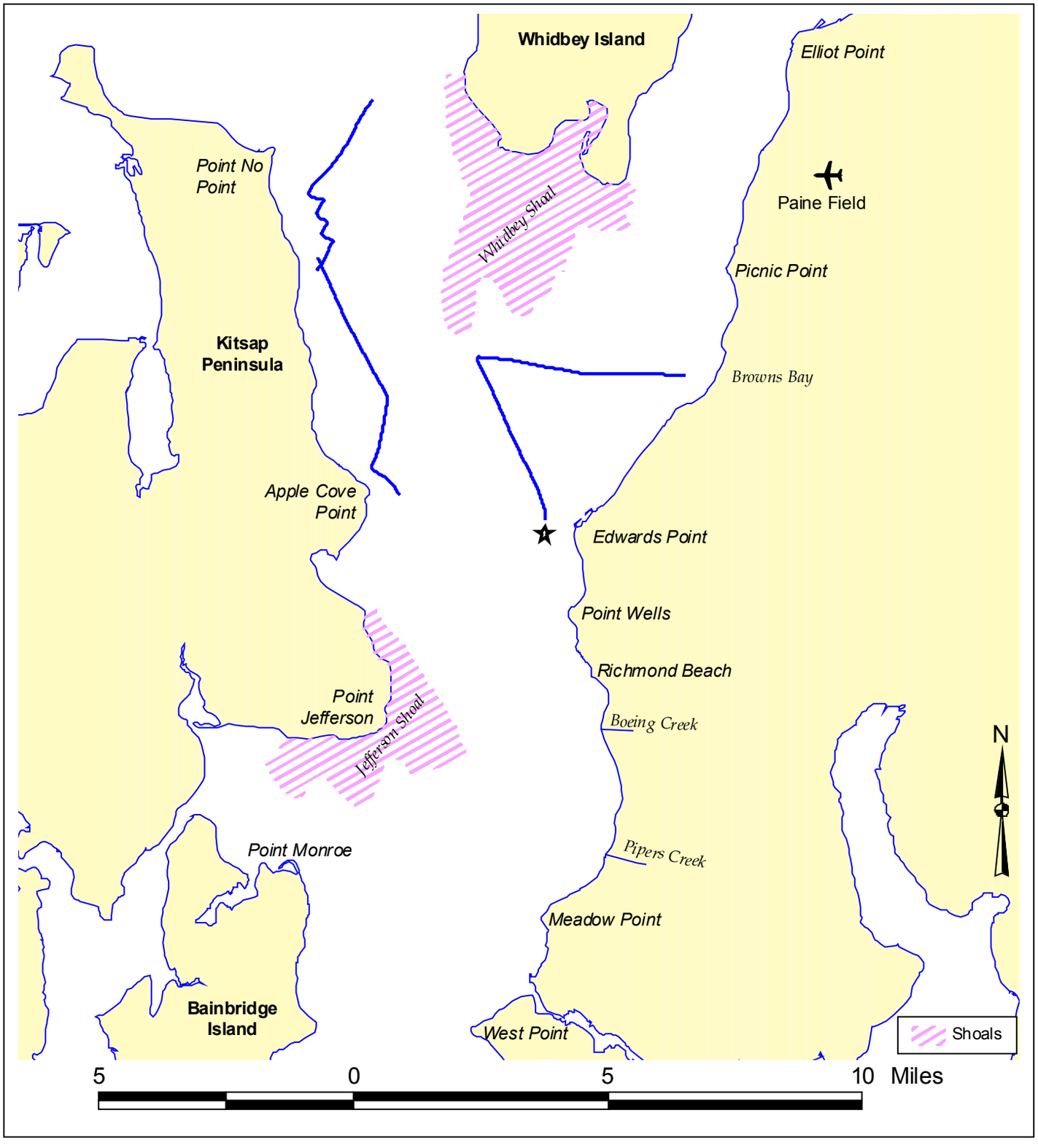
Horizontal path of towed fluorometer during day 2 (February 5, 2002) shown as solid blue line. Red dots represent locations with measured fluorescence levels indicating dye concentrations greater than 0.1 ppb. Black star indicates the dye release location.

Figure G-9G. **Dye Study 5, Day 3 Towed Fluorometer Track**



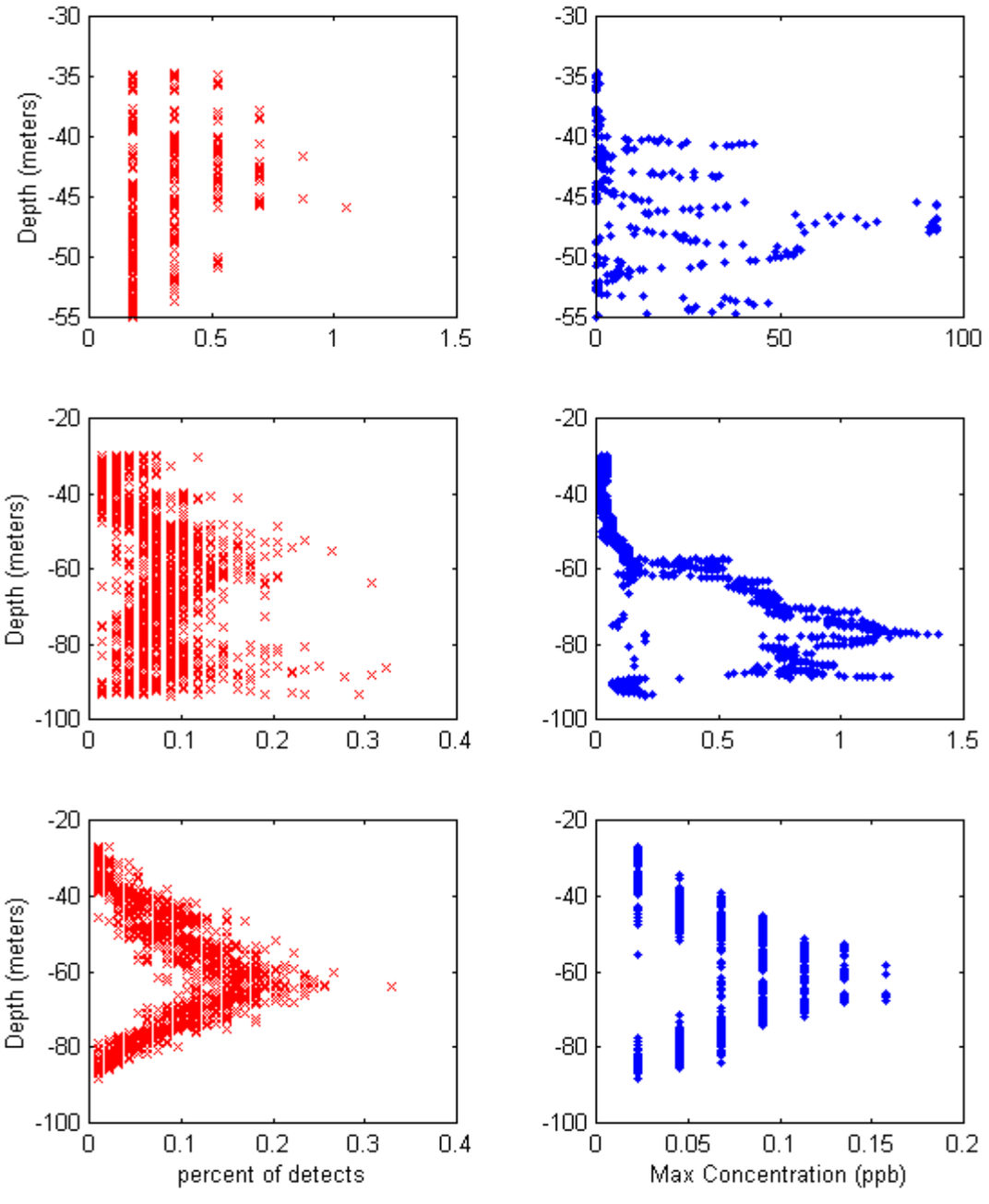
Horizontal path of towed fluorometer during day 3 (February 6, 2002) shown as solid blue line. Red dots represent locations with measured fluorescence levels indicating dye concentrations greater than 0.1 ppb. Black star indicates the dye release location.

Figure G-9H. **Dye Study 5, Day 4 Towed Fluorometer Track**



Horizontal path of towed fluorometer during day 4 (February 7, 2002) shown as solid blue line. No measurements exceeded the detection level of 0.022 ppb. Black star indicates the dye release location.

Figure G-9l. **Dye Study 5, Depth Profile of Dye Observations**



Vertical distribution of dye observations. Left panel shows, of the samples above the detection limit, the percentage that occurred at each depth (total of all depths is 100%). Right panel shows the maximum concentration observed at each depth. Top panels are observations from day 1 (February 4, 2002), middle panels from day 2 (February 5, 2002), and bottom panels from day 3 (February 6, 2002). No dye was detected during day 4.